# A FINE - SCALE ANALYSIS OF NITROGEN USE EFFICENCY OF PADDY RICE SYSTEMS: A CASE STUDY IN ANJI COUNTY IN ZHEJIANG, CHINA

By

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## ABSTRACT

A FINE - SCALE ANALYSIS OF NITROGEN USE EFFICIENCY OF PADDY RICE SYSTEMS: A CASE STUDY IN ANJI COUNTY IN ZHEJIANG, CHINA

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Rice is the staple food in China, especially in the south. Over the last twenty years, nitrogen fertilizer applied in paddy field has been increased considerably to keep up with growing food demand. It is believed that this change has been causing a series of environmental consequences, including groundwater pollution, nitrogen leaching, runoff, and greenhouse gas emissions. Previous studies concluded that most farmers in economically developed areas have been applying too much more fertilizer than crop needs -- hence researchers suggested the government should regulate nitrogen fertilizer useto avoid serious environmental problems.

However, farming practice data used for those studies were aggregated statistical data at or above the county level and, therefore, their conclusions may not be applicable at local or individual farm levels given the spatial heterogeneity in a region. In this research, crop management data was collected at the village level in Anji County in Zhejiang Province, China to examine the spatio--temporal variation of nitrogen use efficiency of paddy rice systems. A biogeochemical model, DNDC, was used to simulate paddy rice systems from 1991 to 2009. The results show that spatial variability had significant impacts on nitrogen use efficiency estimate at county level. Further, as an effort to close the knowledge gap between site-based experiment findings and regional estimation, this study assessed the sensitivity of site-based modeling results to various spatial interpolation approaches. Results indicate that the spatial distribution of paddy field has significant impacts on regional estimates of N use efficiency and must be taken into account for extrapolation of site-specific results to the county level.

## DEDICATION

This thesis is dedicated to my loving parents Maosong Xu & Xuelan Li, for their love, for their endless support and encouragement. It's their dream that I can receive a master degree from a world famous institution, and I hope this achievement will complete their dream.

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# CHAPTER 1 INTRODUCTION

## 1.1 RICE AND ITS CULTIVATION IN CHINA

Rice agriculture systems are some of the major cropping systems in China. There are several different types of rice in China and many systems of growing the rice as well, including paddy rice, lowland and upland rice. These differences represent the different environments rice can be grown in. Of the three, paddy rice is the dominate type in China and in East Asia. According to the report of International Rice Research Institute (Timsina 2007), 93% of total rice fields are irrigated rice paddies, 5% are distributed in rainfed lowlands, and 2% in uplands.

The distribution of paddy rice fields in China is hard to map, because it is a dynamic system. Frolking et al. (2002) generated a 0.5° resolution map (Fig. 1.1) of the distribution of rice agriculture in mainland China. They combined the 1990 county-scale agricultural census statistics and the 1995-1996 optical remote sensing data (Landsat), so the quality of this map is high enough for the purpose of identifying major production areas at the province level. In Fig. 1.1, it is not hard to notice that the majority of rice fields are located in southeast provinces, although we can find some rice fields in northeast and southwest China too.

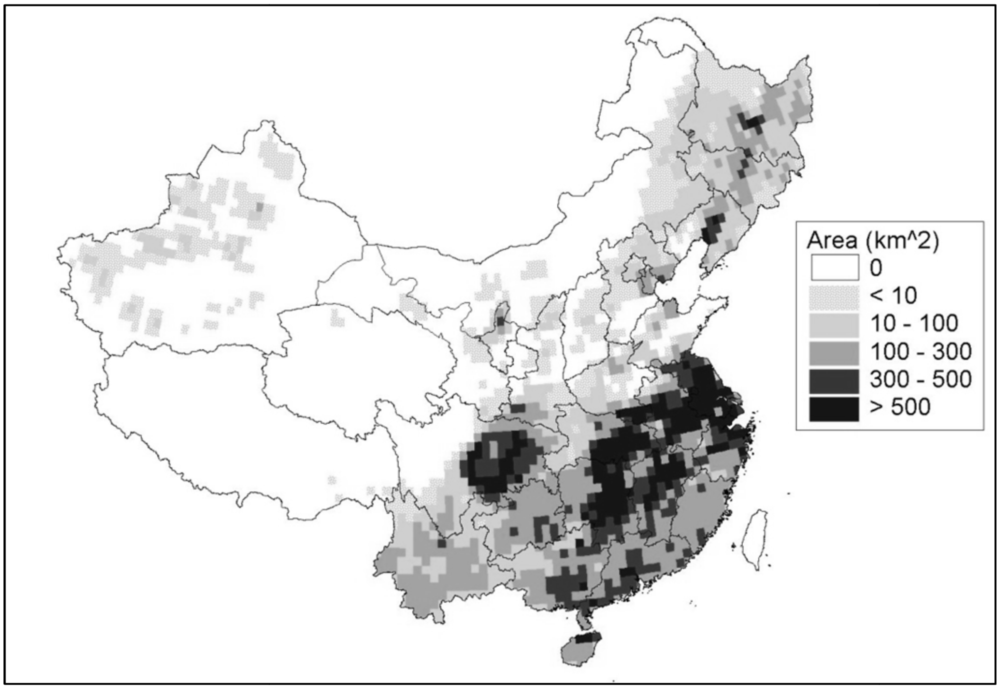
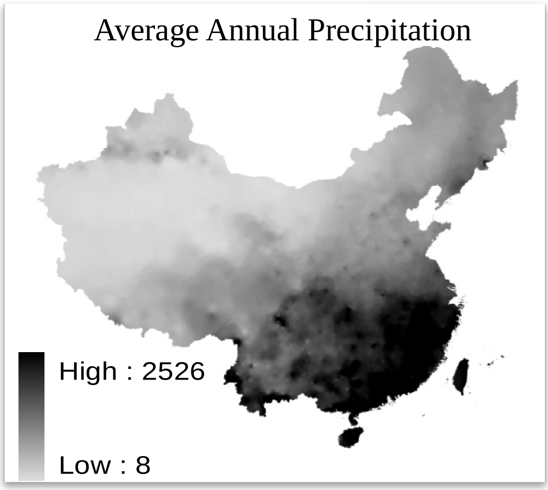


Fig. 1.1 Rice Field Distribution in China (Source: Frolking et al. 2002)

There are many reasons for this distribution pattern, but climate is the most significant one because it largely determines where farmers can grow rice. Cultivation of paddy rice requires a large amount of water and high accumulated temperature (Zhu et al. 2007). Southeast China belongs to the subtropics monsoon climate region, which provides water and sunlight required by paddy rice. To clarify, it is helpful to look at maps of temperature and precipitation distribution in China. Two maps (Fig. 1.2 and Fig. 1.3) were downloaded from the website of Data Sharing Infrastructure of Earth System Science (http://www.geodata.cn), which is a project operated by National Science and Technology Infrastructure Center (http://www.nstic.gov.cn/). It is apparent that southeast China has much more precipitation and accumulated temperature than other parts. Those provinces have been the main paddy rice production areas in China for thousands of years. In fact, the major function of the Grand Canal from Hangzhou to Beijing is transporting grains from southeast china to northern China.



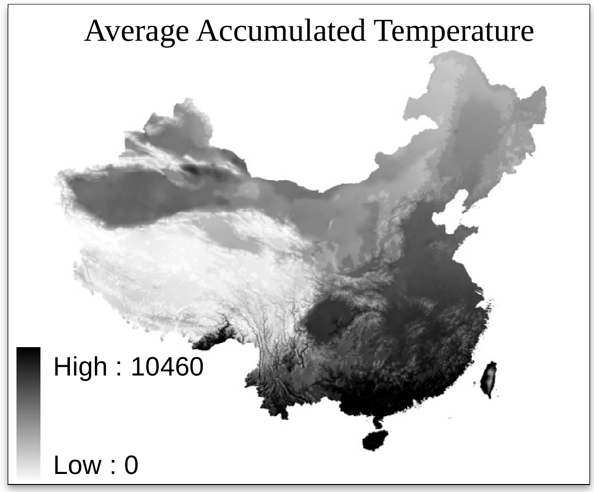


Fig. 1.2 Average Annual Precipitation (mm/year) Fig. 1.3 Average Accumulated Temperature (℃) (Source: Data Sharing Infrastructure of Earth System Science, http://www.geodata.cn )

Besides the climate factor, which roughly corresponds to the distribution of paddy rice fields in China, people might ask why farmers in those provinces still insist on growing rice nowadays. It is true that farmers have other choices like corn or wheat, but it is difficult for those farmers to turn to other species. One of the major reasons is that rice has been planted in this country for thousands of years and rice is a staple of the Chinese diet. In fact, rice was first grown in Yangtze River valley of China (Vaughan, Lu and Tomooka 2008). It is difficult for people to change their traditional food habits. Paddy field is different from other fields like corn fields, and their soil has been improved through long term cultivation. Without significant economic benefits, farmers would prefer rice, since they already know how to cultivate the plant and they can sell all extra grain to the government at a subsidized price.

According to the map illustrated above (Fig. 1.1), paddy rice fields dominate the southeast part of China and most Chinese people live on rice in this area. Take Zhejiang Province as an example: rice contributes around 80% of grain production in this province (Zhu et al. 2007), which means there is a constant need for farmers to maintain and increase their rice yields, due to its essential role as food in the society. As a result, academics are working on various research projects to increase grain yields to support the increasing population of China (Cheng et al. 2007). This is not only a scientific question; it is essential to the security of the Chinese people. According to the 2010 census conducted by the National Bureau of Statistics of China (2010), the total population was more than 1.37 billion. People cannot live without food. Many historical revolutions in China were caused by famines. Thus grain production has direct and significant impacts on social stability (Xu et al. 2006). Under this pressure, it is understandable for the country to try to increase its grain yields.

## 1.2 NITROGEN FERTILIZER USES

Nitrogen (N) is essential to paddy rice systems since it is a required nutrient for crop growth, but N fertilizer application could also cause environmental problems. Fig. 1.4 is a conceptual model of nitrogen circulation of paddy rice systems. External N input includes N from atmospheric deposition, chemical N fertilizer, manure and also crop residue decomposition, but N fertilizer has become the major source of external N supplement in Anji County, according to the field survey conducted by this study. External N input will provide paddy field the necessary nutrients to support paddy rice growth, but not all N applied in paddy field can be utilized by paddy rice. Although soil could fix and hold some of the unused N in the form of soil N storage, unused N still will be lost through gas emissions and N leaching. In fact, greenhouse gas emissions and N leaching are unavoidable, even if N input is insufficient for crop growth; while excessive N input will aggravate N loss. Soil could discharge stored N to paddy rice plants when N input is insufficient, but the effects of this mechanism are limited and it cannot last for a long time since N storage must be supplemented to conserve soil.

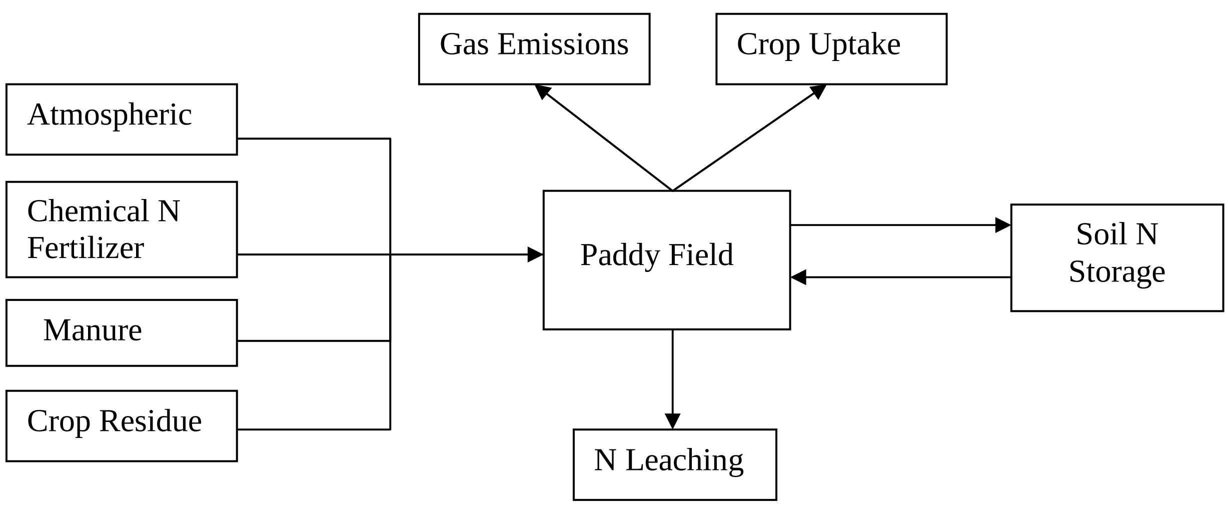



Fig. 1.4 Conceptual Model of N Circulation in Paddy Field

### 1.2.1 Demand of Fertilizer for High Grain Yields

As stated before, it is necessary and important for farmers to maintain and increase their rice yields, due to the essential role of food in a society. The question is how to increase the production of rice? Increasing rice yields per hectare and developing more paddy rice fields are two possible approaches. Theoretically people can accomplish both of them, but it is not feasible in China to develop many more fields because arable land in China is limited. In 2003, only 12.8% of total national terrestrial surface was available for agriculture activities (Chen 2007), and most of it has been developed. To feed its 1.3 billion people with a per capita cultivated land far below the world average, China has already been facing a great challenge of land scarcity. Accelerated urbanization along with explosive economic growth has further worsened the shortage of agricultural land over the last two decades (Chen 2007). Therefore, it is natural for the country to encourage increasing grain yields, including rice yields, per hectare.

From the perspective of farmers, they would prefer to increase crop yields as much as possible. In China, most farmers can only take care of their own fields, although they can rent fields from other farmers if available. In order to earn more income to support their families, farmers would like to increase yields per hectare. There are many factors that could increase yields, such as better rice species (e.g., hybrid rice), or better attendance to their fields. Fertilizer is an important yield-increasing factor. Increasing the amount of fertilizer applied in fields could increase grain yields since crops do need nutrient input and sufficient fertilizer to achieve high yields. However, the benefits from applied fertilizer will be reduced and even diminished when the fertilizer application exceeds the crop uptake capacity (Xuejun et al. 2010).

### 1.2.2 Negative Effects of Nitrogen Fertilizer

While nitrogen fertilizer is essential to achieve high grain yields, it could cause serious environmental pollution, especially if over applied. Researchers reported that rice crops in China consume about 37 % of the total N fertilizer used for rice production in the world, while the area of paddy rice fields is only 20 % of the world's total fields (Peng et al. 2002). Fertilizer application is not a problem if the amount applied matches the demand of plants. However, serious problems can arise if the crop cannot utilize all of the organic or chemical fertilizer N input. Unused fertilizer will be lost and will negatively affect environment quality, either through greenhouse gas emissions or through nitrogen leaching into water bodies. Methane, carbon dioxide, and nitrous oxides are three major types of greenhouse gas emissions produced by paddy rice, and many researchers (Li 2004, Tao et al. 2008, Cline 2007) believe that paddy field is contributing to global warming.

Besides gas emissions, nitrogen could be lost through run-off or leaching. Even for fluxes like ammonia gas ($NH_3$) and nitrogen oxide (NO), part of them will fall back to nearby water bodies through deposition or precipitation. The nutrient elements from agricultural lands will be transported to nearby water bodies and thus increase nitrate concentration in surface water. High concentrations of nitrates in surface water is a threat to the environment because it will contribute to eutrophication --the over-nutrition of a body of water, contributing to the depletion of dissolved oxygen and increase in algae growth-- and the instability of the aquatic ecosystems through possible extinction of plants and animals (Min and Jiao 2002).

### 1.2.3 Effects of Farming Practice

Growing paddy rice requires intensive attendance, which indicates farmers have to monitor growth conditions and make sure their fields have enough water and supplemental nutrients. For the last two decades, farming practice in China has been changed considerably (Zhen et al. 2005). Fertilizer usage and water management are major components of farming practice, because they largely decide the growing conditions for crops, except for soil properties, and they will directly contribute to the change of greenhouse gases emission and nitrate contamination (Li 1995). There are many papers discussing the optimization of farming practice in China (Yagi, Tsuruta and Minami 1997, Li et al. 2006), but the academicians have not reached a consensus yet over this question due to the uncertainty and complexity of farming at different locations. This research is an effort to answer the question of optimal farming practice as well, although indirectly. In fact, it will not try to give a uniform or general improvement suggestion for all farmers; instead this work will assess the impacts of spatial variability on the adoption of farming practices.

### 1.2.4 Are All Paddy Field Over Applied?

There are many papers discussing the problem of excessive fertilizer application and its negative impacts on the environment (Ju et al. 2009, Jun et al. 2004). In the last 20 years, N concentrations in surface and ground water have been increasing. ‘Algae blooms’ in lakes and ‘red tides’ in estuaries occurred frequently, the emissions of nitrous oxide ($N_2O$) and ammonia gas($NH_3$) from farmlands rose (Zhu and Chen 2002). However, most of these studies are site-based (Cabangon et al. 2004) or use aggregated statistical datasets (Li et al. 2006); thus they discarded location attributes in their study. Farming is a complex system which strongly depends on geographical attributes and cannot be bound by simple laws of cause and effect. It is not surprising that soil properties such as fertility will vary at different locations, so the external fertilizer demand for paddy rice will vary spatially as well. However, a detailed geographic survey of nitrogen loss across China or even within a county was not available. It is not a good idea to apply general farming practice conclusions without spatial attributes to all paddy field without considering spatial attributes, since their growth conditions could be very different. In short, it might be too arbitrary to say that all farmers or villages are using too much fertilizer.

It is true that many areas in China have been suffering from environmental degradation including nitrate pollution, but it is unfair to blame farmers only. In the Yangtze River delta, which is one of the three most developed areas in China, the problem of an algae bloom that occurred in Taihu Lake has attracted attention from both the media and researchers. Some researchers believe that the major cause is non-point nitrogen pollution from agriculture activities (Lishan et al. 1997) and their research did show evidence of N pollution of water bodies and N transport from croplands to the water bodies. But, other factors like industrial wastewater pollution and sanitary wastewater could also lead to those problems. Therefore, we cannot identify which one is the major cause of water pollution for a certain area without a detailed survey or a database recording relevant environmental records. Geographically, each location might have a unique situation, and we should investigate this difference before we can make a confident conclusion regarding nitrogen usage strategy for a large area.

Another misunderstanding of nitrogen fertilizer is the so-called "upper limit level" or suggested level for Nitrogen fertilizer applied per hectare. Some papers mentioned that the suggested upper level of fertilizer usage in paddy field is 225 kg N/ha (Tao 2006), but is this really appropriate? Crop nitrogen uptake depends on crop demand and uptake capacity. According to Zhang et al. (2002), nitrogen demand includes deficiency demand and new growth demand, and nitrogen uptake capacity depends on mineral nitrogen concentration in root zone and soil moisture. Those factors are dynamic factors, and therefore it is hard to give a suggested number. A suggested ‘optimal’ number probably works well in some areas for a certain crop, but it is hard, if not impossible, to define such a threshold for a large area like a province, or even for a county. As the soil properties and paddy rice species change, the N uptake capacity and the amount of N loss will be varied greatly (Zhang et al. 2002). Noting that grain yields in China for the last twenty years have increased significantly, it is necessary to investigate nitrogen loss from paddy rice systems more thoroughly than just draw a “general” conclusion and then recommend that all counties adopt it. If a county does not actually have sufficient input and they adopt the suggestion to reduce N fertilizer application, it could cause unnecessary rice yields loss and hurt farmers.

## 1.3 RESEARCH AREA

### 1.3.1 Zhejiang Province

Zhejiang Province is located in the Yangtze River delta, which is one of the three most developed areas in China. This province is a traditional paddy rice producing Chinese province. In fact, it has been the homeland for fish and rice production for thousands of years. According to the Statistic Year Book of Zhejiang Province, released by the Statistics Department of Zhejiang Province (2010), the province had 1.29 million hectare farmlands and 0.938 million hectares were paddy rice fields by the end of 2009, which accounts for 75% of the total farmlands.

### 1.3.2 The Reasons to Select Anji County

Zhejiang province is densely populated, and the arable land in the province is limited. As a result, it is a challenge for this province to keep up with food demand, and Anji County is a standard county in Zhejiang Province facing this challenge. According to the official website of Anji County Government (2010), Anji had around 457,060 people by the end of 2009, and the area for this county is about 1,886 $km^2$. Therefore, the population density for the county is around 242/$km^2$, which is 74% higher than the national average population density, according to the data given by the National Bureau of Statistics of China (2010). Limited arable land in the county makes this problem even worse. A census of agriculture conducted by Anji County Government (2006) indicates the county has only 186.46 $km^2$ of arable land, which is less than 10% of the total area of the county. As a result, the arable land per person for this county is only around 0.04 ha, while the national average level is 0.942 ha (Zhu and Zhang 2007). Because the county has less arable land per person than other counties, it seems that farmers in this county may need to increase the amount of fertilizer applied in fields to meet the growing demand for food. Thus Anji County is a good study area to examine whether it is diverse or not in regards to fertilizer usage and its efficiency.

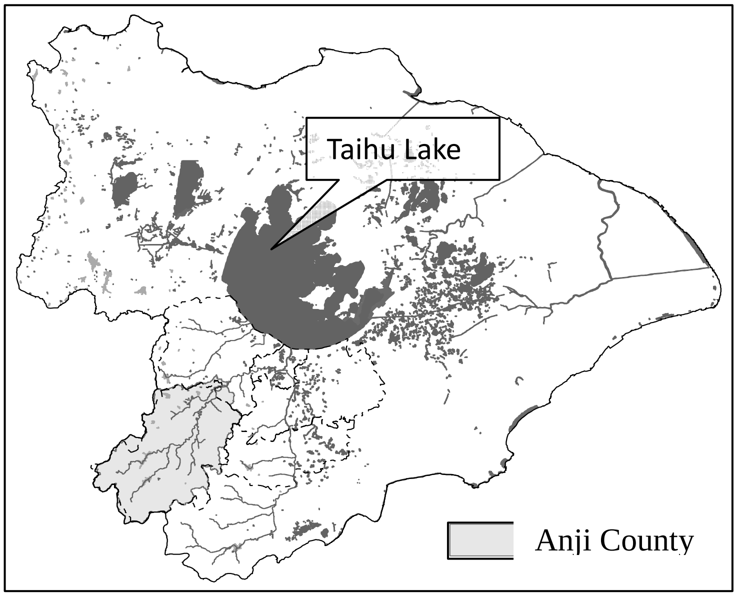



Fig. 1.5 West Tiaoxi River Watershed and Taihu Lake (Li, Liu and Yang 2004)

Another important factor is environmental pollution caused by nitrogen loss in Zhejiang province. In Fig. 1.5, Anji County is the gray-shaded area, which is close to Taihu Lake. This lake is an important water body in this region, because the Taihu Lake plain is famous for paddy rice production in China. However, the water quality in this lake has been decreasing for many years. In fact, the problem of green-blue algae bloom occurring in Taihu Lake has attracted attention and investigation of researchers. Some researchers believe that the major cause is non-point nitrogen pollution from agriculture activities (Wang et al. 2003). In addition to the nearby farmlands, rivers in the region will also contribute pollutants to the Lake. The Tiaoxi River is one of the main contributors of water volume inlet and outlet of Taihu Lake. Accord to Wang et al. (2010) , inlet water quantity of the Tiaoxi River accounts for over 60% water quantity of the total region water inlet. Anji County is located on the west Tiaoxi River watershed and, therefore the water quality of west Tiaoxi River in this county is also very important.

In summary, the need for high grain yields is strong in this county, but environmental issues like Tiaoxi River watershed pollution is also a serious concern. As a result, this study selected Anji County in Zhejiang Province as the study area, since it is a typical county in this province facing the challenge of fighting hungry and protecting their environment.

## 1.4 RESEARCH OBJECTIVES

How can the constant need for high grain yields and the rising need to protect the environment in Zhejiang Province be balanced? Should we give priority to grain production or environment protection? Indeed, it is hard to give a general answer to those questions without specific research because the situations between villages might differ. Take Anji County as an example; should we limit or suggest constant limits on the amount of fertilizer applied per hectare across this county? If researchers look at the aggregated statistical data alone, the county as a whole might appear to be using too much fertilizer. However, that does not mean all villages should limit their fertilizer usage, since it is not impossible that many villages indeed need more fertilizer. Thus, it is necessary to perform a thorough study in Anji County.

First, this study will identify the impacts of farming practice on N efficiency and environmental pollution in Anji County tempo-spatially. As in other places, the farming practices in Anji County have changed considerably, so this study will use a biogeochemical model to simulate paddy rice systems using historical management and climate data. As discussed above, this research is expected to disprove that fertilizer utility in most villages declined since 1990s, and that greenhouse gas emissions and N leaching increased because fertilizer application increased since then.

The second objective of this research is to tempo-spatially examine the diversity of N fertilizer use efficiency on paddy field within Anji County. This includes discussions of N demand, N deficiency, if any, and N loss. This research is expected to find evidence to demonstrate that the variations of N use efficiency between villages within the same county could be significant. Previous studies used aggregated statistical data ( Li et al. 2004) with the finest resolution at or above the county level (Zhang et al. 2009b). But is the county a fine enough unit? In other words, will spatial variation within a county affect N efficiency estimation significantly? If there is no significant difference, then future research can simply use aggregated statistical data, otherwise it will be necessary to take spatial variations into consideration in future research. This study will answer those questions.

# CHAPTER 2 LITERATURE REVIEW

## 2.1 RESEARCH ON NITROGEN LOSS OF PADDY RICE

China is one of the major countries producing rice in the world. The demand for rice continues to rise because of continuous population growth, which results in more frequent applications of fertilizers in rice production. Therefore, environmental pollution caused by nitrogen (N) leaching or runoff from farmlands has become a major concern (Ju et al. 2009). Chinese farmers had been using organic manure as fertilizer for a very long time, but the traditional practice has been changed during the past decades because chemical fertilizer is more efficient and convenient to use. Most rice fields in Zhejiang Province have received very little manure for many years (Zhang, Wang and Xie 2006).

Since the 1980s, nitrogen fertilizer consumption in China has increased substantially (Liu, Wu and Zhang 2005). China consumed $1.74*10^7$ Mg of N in their chemical fertilizer in 1990 and $2.22*10^7$ Mg of N in 1995 (Xing and Zhu 2000), which accounted for one-fourth of the world total at that time. N fertilizer helps increase grain yields, but the benefits from applying fertilizer will be reduced when the amount of fertilizer applied exceeds the crop uptake capacity. Xuejun et al. (2010) carried out a field experiment in the Yangtze River and Yellow River Delta areas to study water and N use efficiency of rice systems. Their study indicated that the N use efficiency decreased as N rates used in fields increased. Nitrogen fertilizer could cause environmental pollution, especially if over-applied in paddy field. Greenhouse gas emission and N transportation to water bodies in China has become an important issue, receiving great attention from both local and overseas scientists (Liang et al. 2007).

Nitrogen fertilizer could be a threat to the environment because unused N in farmland will be lost and will negatively affect environmental quality, either through greenhouse gas emissions or through N transport to ground and surface water bodies (Xing and Zhu 2000). In paddy field, applied N could be lost during the processes of nitrification and denitrification. According to Majumdar (2009), ammonium N in fertilizers, once applied in paddy field, is nitrified in the oxidizing layer, at the water-and-soil interface, forming $NO_3$, which moves downwards to the reducing layer and there becomes denitrified (Xing et al. 2002). Methane, carbon dioxide, and nitrous oxide are the three most important gases emitted from paddy field. The amount of greenhouse gases emitted from paddy field varies across time and location, but basically it is believed that paddy rice systems have been contributing to global warming (Li 2004, Tao et al. 2008, Cline 2007).

Besides contributing to gas emissions, nitrogen fertilizer could also be lost through N leaching. Researchers believe that inappropriate nitrogen fertilizer usage will aggravate N leaching and thus contribute to non-point nitrogen pollution: the nutrient elements from agricultural lands will be transported to nearby water bodies and thus increase nitrate concentration in surface waters. High concentrations of nitrates in surface water is a threat to the environment because they will contribute to eutrophication -- the over-nutrition of a body of water, contributing to the depletion of dissolved oxygen and increase in algae growth (Min and Jiao 2002). Also, Lishan et al. (1997) found the load of nitrate to shallow groundwater increases as the N fertilizer application increases. In fact, researcher believe that nitrates from agriculture systems have been one of the major pollutants leaching to groundwater (Liu et al. 2005). However, other factors like industry wastewater and sanitary wastewater pollution could also lead to those problems. For instance, a study conducted in Jiangsu Province, which shares Taihu Lake with Zhejiang Province, examined the water samples collected in this area (Xing et al. 2001) and they found that $NH_4^+$ is the dominant pollutant. Their study indicated that agriculture activities in their study area was not the major cause of nitrogen pollution, because the high content of $NH_4^+$ in water bodies usually does not come from farmlands.

Generally, it is believed that intensive farming systems, like paddy rice systems, with high N rates applied in fields have been contributing to environment pollution (Liu et al. 2005). Therefore, some researchers suggested to the government that they formulate agricultural policies related to N fertilizer usage to encourage farmers in economically developed areas to reduce N rates applied in fields (Ju et al. 2004). However, many of these studies adopted results from a few sites to represent larger regions (Ju et al. 2009, Wang et al. 2004) or used aggregated statistical datasets at or above the county level (Li et al. 2006). As stated before, farming systems are complex systems, and spatial heterogeneity of anthropogenic activities and crop growth environments should be considered. Researchers have found that soil physical properties and also nutrients contents varied significantly spatially (Fulton et al. 1996, Gupta et al. 1997). Experiments conducted by Inamura et al. (2004) indicated that crop yields, soil properties and crop management datasets for paddy rice systems can vary significantly even within small study area. In this case, the external fertilizer demand for a paddy rice field will also be different, because N supply or N storage in soils is different. According to Sadler (1998), fine scale spatial data is necessary for precision farming. Without detailed analysis of crop growth conditions at fine scale, it is probably not a good idea to apply general conclusions obtained from a few sites to all paddy field since their situations could be, and likely are, different. In a word, it might be too pessimistic to say that all farmers or villages are using too much fertilizer.

Agroecosystems are complex; they include factors such as crop choice, soils quality, atmosphere and farming practices. Field experiments and broad statistical studies are usually too simplistic to integrate all components well. In contrast, dynamic modeling is a more effective solution to integrate various processes. Also, as Zhang (2002) indicated: "a model can be used as a tool for mechanism understanding, estimating, predicting, and policy making" (p 76). Therefore, in this research, a dynamic modeling approach will be adopted to explore the diversity of nitrogen fertilizer efficiency of paddy rice systems in Anji County, Zhejiang Province in China.

## 2.2 BIOGEOCHEMICAL MODELING FOR AGROECOSYSTEMS

### 2.2.1 Model Comparison

As stated before, agroecosystems like paddy rice systems are complex and dynamic modeling is an effective solution to simulate them. There have been many modeling studies around agroecosystems in the fields of agronomy, climatology, and environmental studies, although their purposes, approaches and scales are quite different.

In general, agronomists usually focus on crop growth and yield formation, and their models are called crop growth models, such as DSSAT (Tusji, Uehara and Balsa 1994), RCSODS (Gao et al. 1992). Those models were developed to help maintain high crop production and efficient management, especially for water and fertilizer management (Zhang et al. 2002). The emphases of these models include crop growth, development and soil water dynamics; but soil biogeochemistry was rarely considered or simulated in detail. Alternatively, models designed to assist environmental studies usually focus on element and material cycles to understand the interaction of anthropogenic activities and the environment. These models are usually termed as biogeochemical models because they take soil processes into account, such as decomposition, nitrification and denitrification. Examples of these models include RothC (Jenkinson et al. 1990) for carbon turnover, CENTURY (Parton, Stewart and Cole 1988) for carbon, nitrogen, sulphur and phosphorus cycles, and MEM (Cao, Dent and Heal 1995) for methane emissions (Zhang et al. 2002). While crop and environmental models pay more attention to ground and underground processes, climate models usually emphasize the interaction of land surface with the atmosphere, such as the famous BATs model (Dickinson et al. 1986) and Noah Land surface Model (Chen and Dudhia 2001). Although these models do include land surface parameters, they were developed to simulate atmospheric physics processes, such as radiation, water, heat and momentum fluxes.

### 2.2.2 The DNDC Model

The DeNitrification-DeComposition (DNDC) model is a process-based biogeochemical model that initially focused on trace gas emissions from agroecosystems (Li, Frolking and Frolking 1992a, Li, Frolking and Frolking 1992b). At first, the model was designed to simulate $N_2O$ and $CO_2$ emissions from crop lands. The model has since been expanded to simulate NO, $N_2O$, $CH_4$, $CO_2$, and $NH_3$ emissions (Li 2002). Currently, the DNDC model (Version 9.4) is a process-based soil biogeochemical research tool that was developed to estimate the impacts of farming management strategies on the nitrogen (N) and carbon (C) circulations in agro ecosystems (Li 2002, Li 2004, Li et al. 2006).

Using this model, environmental impacts such as climate change, land-use change and agricultural activities including alternative farming practices, on crop production and greenhouse gas emissions can be assessed in a comprehensive way (Li 2007a). It integrates daily crop growth processes with soil biogeochemical processes and simulates important processes related to N and C cycles in plan -- soil systems, including mineralization, ammonia volatilization, nitrification, denitrification, N uptake, and N leaching (Smith et al. 2010).

To enable the DNDC model to simulate C and N biogeochemical cycling in paddy rice systems, Li and his colleagues modified the model by adding a series of anaerobic processes (Zhang 2002, Li 2004, Cai 2003). Specifically, a detailed rice growth sub-model was developed for the DNDC to quantify three dynamic parameters crucial for modeling gas production and oxidation: total rice biomass, root development and biomass, and rice parenchyma development (Zhang et al. 2002). Fumoto (2008) also revised this model to simulate crop growth and soil processes more explicitly and improve its ability to estimate methane ($CH_4$) emission from rice paddy field under a wide range of climatic and agronomic conditions. The DNDC model has been tested against several methane flux data sets from wetland rice sites in the U.S., Italy, Thailand, the Philippines, India and Japan; and was generally consistent with field observations (Li 2002, Babu et al. 2006, Fumoto et al. 2008).

In China, scientists have studied paddy rice systems, including trace gas emissions, using the DNDC model for many years. Zheng et al. (1997) used the DNDC model to simulated $CH_4$ emitted from 25 paddy field of Wu County in the Jiangsu Province, China, and the simulated results were in agreement with measured emissions. Cai et al. (2003) also simulated methane emitted from rice fields at different regions using the DNDC model and they found the model could capture methane emissions well. Zou (2009) simulated fertilizer--induced $N_2O$ emissions from paddy field in China between the 1950s and 1990s. The model has been revised to include the ability to simulate paddy rice system in the last few years, and the performance of the model has been discussed in several papers (Cai 2003, Li 2004, Li et al. 2006).

## 2.3 HIGHLIGHTS OF THIS RESEARCH

Previous studies related to nitrogen loss and fertilizer efficiency in Zhejiang Province are limited: researchers in Zhejiang province currently tend to focus on site specific nitrogen management (Peng et al. 2011). Site-specific nutrient management (SSNM) is a method advocated by researchers recently, and field experiments confirmed it could reduce nitrogen loss in the study area. Those studies will help farmers to achieve better nitrogen fertilizer use efficiency. The limitation of this method is that it could not predict the areas that need to improve their farming practices, because SSNM has to conduct experiments on every site to be studied. This empirical approach is hard to popularize because crop growth conditions for various fields might be significantly different. In contrast, computer crop models could simulate historical scenarios and also predict future scenarios with appropriate datasets, without field experiments. Thus it is possible for researchers to do tempo-spatial analysis.

Regional studies conducted in China using biogeochemical modeling are becoming more and more popular (Liang et al. 2007, Zhang et al. 2009a). These studies could reflect the situation in Zhejiang Province to some degree. For example, Wang et.al (Wang, Ouyang.Zhiyun and Miao 2001) simulated $N_2O$ and $CH_4$ emission in Yangzi river delta in 2001, and they validated DNDC model could capture gas fluxes from farm lands in this area. However, their research did not focus on paddy rice. More importantly, they used county as the basic unit for their studies, and the differences within a county were ignored. Li and his colleagues (2004) did a case study for water management of rice agriculture of China. This study covered major provinces producing paddy rice, but the farming management data they used were estimated from the county level statistical datasets and the soil map digitized is a coarse national soil map. Those studies might be good for estimating the overall trend of crop growth and nitrogen loss for a large area, but they failed to tell the spatial variance within a county.

Thus, gaps exist between previous studies and the need to understand N usage of paddy rice systems and its impacts on the environment. There is an inconsistency between studies on sites and regional studies in regards of spatial resolution and study method. Site- based studies usually achieve more accurate results since they can utilize more detailed datasets and simulate crop growth for a site in detail. But studies which focus on certain fields cannot depict the big picture for a large region, such as a county or a province. To understand the general trend of nitrogen usage and its environmental impacts in China, researchers conducted studies for various regions in the country. However, the finest geographic data resolution for previous regional studies is at the county level (Li et al. 2010, Tang et al. 2006, Liu et al. 2006). Using aggregated statistical data can not reflect the diversity of N usage and spatial variation of crop growth environments, including soil properties and weather conditions in the study area. While many papers have validated crop models like the DNDC in paddy field (Babu et al. 2006), they were actually validations of the model itself or the improvement of the parameters used for the model, rather than a test of the impacts of diverse N usage on nitrogen efficiency or nitrogen loss studies. If N usage varies greatly within a county, it might be too subjective to draw a conclusion for a region based on previous studies. For instance, some villages in a county might apply more fertilizers than needed, while other farmers use less fertilizer than needed.

As an effort to bridge gaps between current site and regional studies, this research will use detailed datasets at the village level to identify the spatial variations of crop growth environments and farming practices within the same county, and their impacts on N efficiency and N loss studies. In this way, it is possible to assess the potential uncertainties and variations associated with paddy rice systems and N usage at different scales. It is hoped that this research could help paddy rice systems' research using biogeochemical modeling to integrate geographic attributes of farming activities more effectively in the future.

This research will study nitrogen fertilizer usage of paddy rice system in a more comprehensive way. Previous studies usually focused on greenhouse gas emissions, such as $N_2O$ or $CH_4$, and tried to link fertilizer usage directly with gases emissions (Fumoto et al. 2008). Secondly, previous studies tended to compare the amount of fertilizer applied per hectare. It is true that fertilizer applications have increased significantly; but the nitrogen uptake capacity for paddy rice also increased greatly since new species have much higher grain yields, and soil conditions can cause variations in external fertilizer demand. Furthermore, previous studies suggested that change of farming practice over the last decades in China have been leading to non-point agriculture environmental pollutions but they did not provide sufficient evidence to prove it. In this research, we will separate changes in farming practice, particularly fertilizer usage, from climate change. In this way, the impacts brought of farming practice and climate change can be assessed separately.

Finally, previous studies used hypothetical data to test the impacts of alternative farming management practices on crop growth and the environment (Wang et al. 2001, Li et al. 2006, Li et al. 2010). This is convenient for comparative analysis, but subjectively created numbers cannot help people to understand how changing historical farming practices have affected the environment. So this research will use real historical farming management datasets obtained through field survey to assess the impacts spatio--temporally of farming practice, particularly fertilizer usage, on the environmental costs of paddy rice systems.

# CHAPTER 3 MODEL DESCRIPTION AND DATA PROCESSING

## 3.1 MODEL DESCRIPTION

As discussed in the literature review, biogeochemical modeling is becoming more and more popular for studies focusing on the interaction of agriculture activities and the environments. In this research, a biogeochemical model – the DNDC model – was selected to simulate paddy rice systems in Anji County. This model has been widely validated in many countries including China. Previous publications indicated the applicability of the DNDC model for paddy rice research. Thus the DNDC model was selected as the study model for this research.

The DNDC model was developed by Li and his colleagues (Zhang 2002) at the University of New Hampshire, for predicting crop yield, soil carbon sequestration, nitrogen leaching, and trace gas emissions in agro-ecosystems. The Denitrification-Decomposition (DNDC) model is a process-oriented computer simulation model of carbon and nitrogen biogeochemistry in agro-ecosystems. Classical laws of physics, chemistry and biology, as well as empirical equations generated from laboratory studies, have been incorporated in the model to parameterize each specific geochemical or biochemical reaction (Li 2007b). The model has been revised several times since the first version (Li et al. 1992, 1994, 2005). Version 9.4 is the latest version and it was used as the model for this research. Users can download this model freely from the official website of the DNDC model (http://www.dndc.sr.unh.edu/).

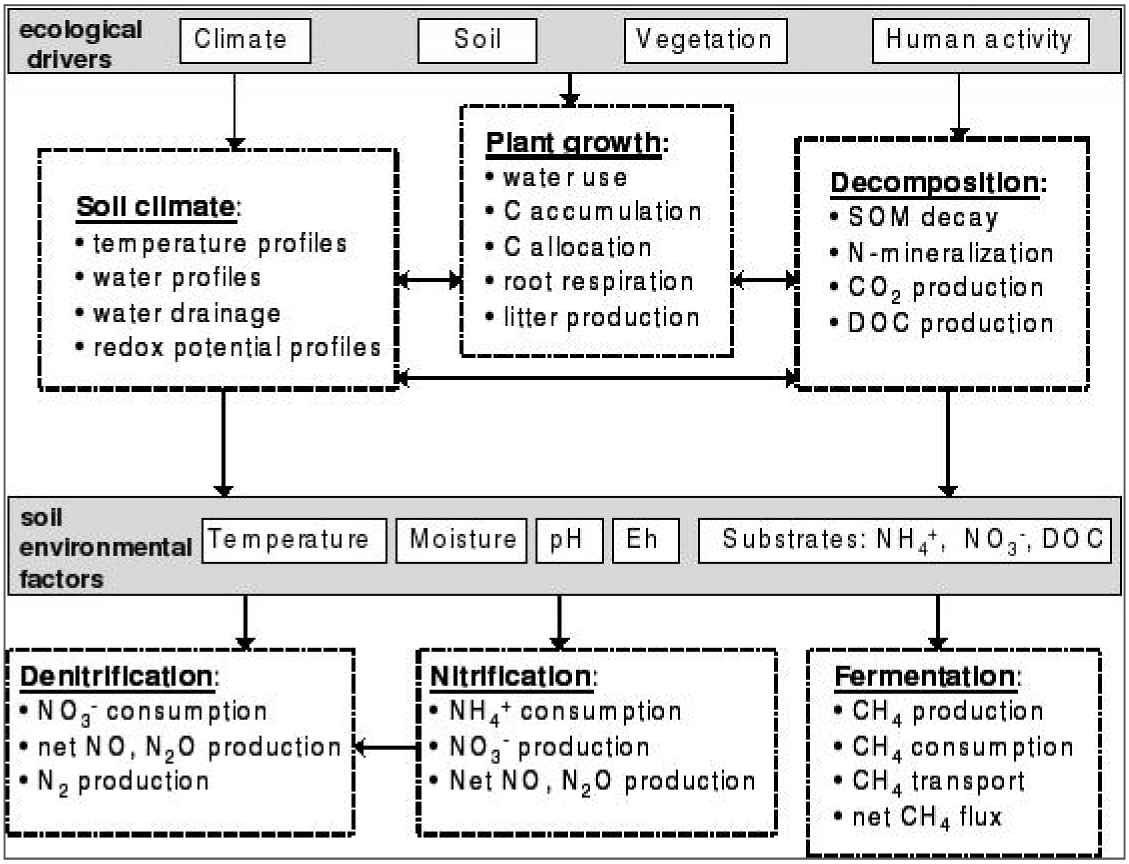



Fig. 3.1 Structure of the DNDC Model (Salas et al. 2006)

The DNDC model integrated various processes, and these processes can be grouped into two components - ecological drivers and biogeochemical sub- models. Fig. 3.1 is the illustration of the model given by the User's Guide of the DNDC model (Li 2007b). The entire model is driven by four major ecological drivers, namely climate, soil, physical properties, vegetation, and human activities. A highlight of this model is the sub model of human activity, which allows users to define in detail the farming practices for a certain crop. Soil biochemistry sub models will respond to these drivers. In this way, the model will integrate the C and N biogeochemical cycles and the primary ecological drivers. Any component in the system could affect the performance of the DNDC model, but input data usually plays an important role. Thus it is necessary to obtain appropriate input data for this research, which will ensure the success of paddy rice system simulations, particularly at site scale.

## 3.2 DATA COLLECTION AND PROCESSING

### 3.2.1 Farming Management Data

Data about detailed farming practices at the village level in Zhejiang Province is not publically available. The agriculture census conducted by local government did not pay attention to the details of farming practices. In Anji County, there are some census datasets on the websites of Anji Statistics Bureau (http://www.ajtj.gov.cn/), but those datasets are aggregated statistical data without geographic attributes. But data at the village level is necessary because the objective of this study is to identify the impacts of spatial variations of both human activities and natural environments on modeling predictions. Thus, instead of employing county level statistical data as previous studies did, researcher went to Anji County during the summer of 2010 to collect the first hand farming practice data for the study area through interviewing local farmers and officers.

Fig. 3.2 Paddy Rice Field and Selected Villages

There were 169 villages in Anji County, the total area of which was about 1,886 $km^2$ by the end of 2009, according to the official website of Anji County Government (2010). With restrained budget, it is not practical to visit and interview farmers in every village. Instead, 18 typical villages, which are dark dots in Fig. 3.2, were selected from the county, and these villages were visited one by one. The typical village in Anji County is large and surrounded by paddy rice fields, which are gray-shaded patches around villages in Fig. 3.2.

For each village, the location of the visiting point is recorded on the map, and then geocoded. A special survey form was designed and data was collected through interviews with local officers and/or farmers. Some villages have a committee which has an office in charge of agriculture activities. In this case, local officers were interviewed first since they have years of experiences with local paddy rice planting and they have better access to related information for the region than individuals. For villages without such an office, village heads and big farming households were selected for interviews.

The survey form was designed to capture major aspects of paddy rice farming practice, namely crop type and rotation, tillage, fertilization, manure amendment, irrigation, flooding, weeding, grazing and grass cutting. It also recorded the historical grain yields per mu, which is equivalent to 0.067 ha. The form was designed to collect sufficient information to run the DNDC model at site scale. Survey data were then processed and input into the DNDC model manually. The model has a graphic interface for users to fill out required fields.

Potential problems associated with the survey could be the quality of data collected from local farmers. The time span for this research is 1990 to 2010, with 5-year intervals; so only 1990,1995,2000,2005 and 2010 will be estimated. Real data records are desired, but none were routinely recorded data for each village within the same county; thus it is impossible to get accurate historical data. The researchers tried to obtain estimates from local farmers, although it is hard for farmers to remember details of farming practice clearly, especially more than 10 years ago. Fertilization, manure, and grain yield are the most important components and farmers usually remember them better than other details. The remaining components, such as water management, required by DNDC model are asked for only recent years, which is easier for farmers to recall and help the researchers to understand the actual situation of farming practices in visited villages. To eliminate extreme values and capture the general situation for a village, a local activity center, such as a grocery store or committee in the village, were selected to conduct the interview. At least 5 farmers participated in group discussion and they tried to decide on an estimation accepted by the group.

### 3.2.2 Soil and Boundary Data

Fig. 3.3 is the administration boundary of Anji County. The map is digitized from a paper map published by local government. Digitizing is not sufficient to perform spatial analysis because we need a spatial reference, such as a coordinate system, to locate geographic entities. So the digital soil map was used as the reference map to do the geo reference using ArcGIS 9.3. The geographic coordinate system used by the soil map is GCS_Xian_1980 and the projection employed is Gauss_Kruger.

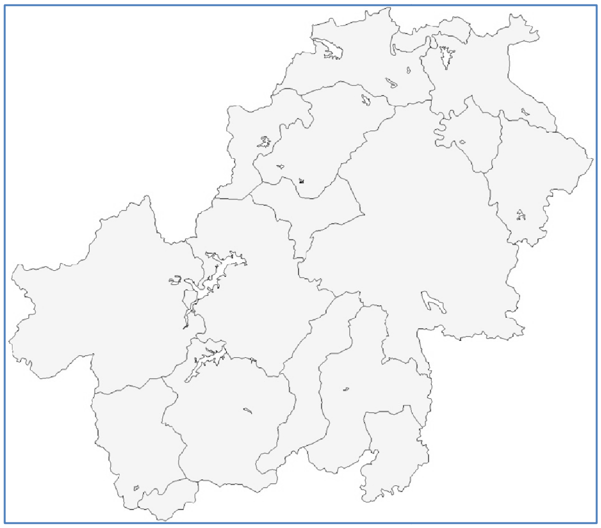


Fig. 3.3 Administration Boundary of Anji County

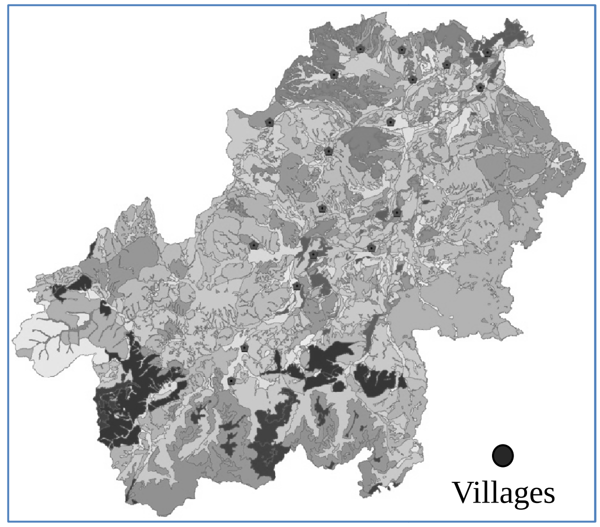



Fig. 3.4 Soil Map

Previous studies (Li et al. 2005, Li et al. 2006) usually utilized the national soil survey database produced by Institute of Soil Science, Chinese Academy of Sciences (Shi et al. 2004). This data is a raster format soil map with a 10 km spatial resolution, which is not detailed enough in order to understand the diversity of soil properties within a county. For example, only 20 raster units can be found in Anji County. Fortunately, a detailed vector soil map (Fig. 3.4) with associated soil properties was kindly provided by Dr. Jiaping Wu at the Environmental Remote Sensing Lab of Zhejiang University. Soil data is an important component for agriculture ecosystem research because soil properties could affect plant growth and environment costs significantly.

Major soil properties required by the DNDC model include soil organic content, soil pH value, texture classification, clay fraction, bulk density, field capacity, hydro-conductivity, wilting point and porosity. For this research, land-use type will be paddy rice only. Given land-use type and soil texture and soil organic content values, the DNDC model can fill out other fields automatically. The slope will be left as zero because slope calculation using the SRTM map and DEM (Digital Terrain Map) for Anji County indicates that paddy field (Fig. 3.2) in this county is located in a plain area (Fig. 3.5). For each village, a unique input profile of soil properties and cropping management will be created. The problem with the digital soil map is that it does not include field capacity and wilting point values. In order to utilize the soil data in the DNDC model, the SPAW (Soil-Plant-Atmosphere-Water field and Pond) Hydrology model (Saxton and Rawls 2006), provided by USDA and Washington State University, was used to calculate field capacity and wilting point values using other parameters; specifically, Soil Water Characteristics, which is a sub model of the SPAW model, was employed directly to do this job. This model derives soil water characteristics from soil texture properties. For field capacity and wilting point, they use regression equations based on values of clay fraction, sand fraction and soil organic content.

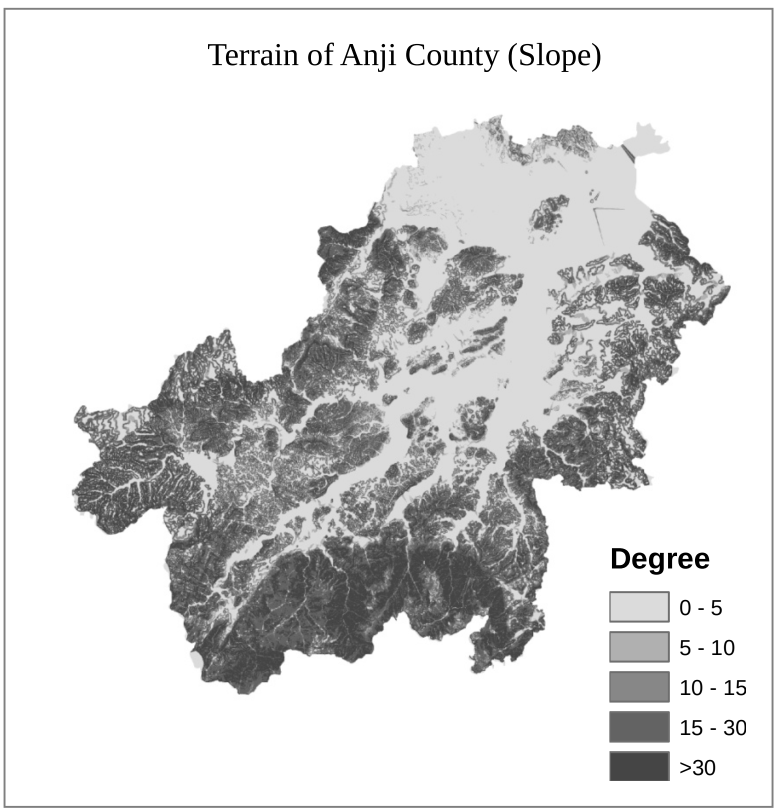



Fig. 3.5 Terrain of Anji County

### 3.2.3 Land Use and Land Cover Data

Currently there is no publically available land use and land cover datasets for Zhejiang Province or Anji County with detailed classification. For this research, Landsat 5 TM images were selected as the input data for further classification and interpretation. Images were downloaded from the website of USGS using the GeoVis tool (http://glovis.usgs.gov/). Three images, including 1991, 1994 and 2001 were downloaded.

The paddy rice systems are dynamic systems, and growing dates differ from village to village. Thus it is very difficult to include all fields in one remotely sensed image. Examination of available images for Anji County from USGS indicated that May through July is the optimal time to capture most paddy rice fields because it is easier to differentiate between paddy field and other farmlands. For this reason, three images taken during that time period were selected to obtain paddy field distributions for the years 1991, 1994 and 2001 respectively.

Table 3.1 Selected Remote Sensed Images

| Acquisition Date | Platform | Pixel Size | WRS_Path | WRS_Row |
|---|---|---|---|---|
| 1991-07-23 | Landsat 5 TM | 30m | 39 | 119 |
| 1994-05-12 | Landsat 5 TM | 30m | 39 | 119 |
| 2001-07-26 | Landsat 5 TM | 30m | 39 | 119 |

Digital images were then processed using ERDAS imaging software. Radiometric and atmospheric corrections were conducted first. Details of radiometric calibration and relevant coefficients can be found in Chander's paper (Chander, Markham and Helder 2009). Atmospheric correction is an important preprocessing step required in many remote sensing applications because a reduction in scene-to-scene variability can be achieved. The objective of atmospheric correction is to convert remotely sensed DN (Digital Numbers) to ground surface reflectance. Specifically, CosT model (Chavez 1996) was used in this research, which has been validated and suggested by Lu et.al (2002) to perform atmospheric correction. After that, pixels were classified using unsupervised classification method provided by the software to identify paddy rice fields in the county. The algorithm used for unsupervised classification is the well known ISODATA, which stands for Iterative Self-Organizing Data Analysis Techniques (Jain, Murty and Flynn 1999).

Total area of paddy field obtained from remote sensed images is compared to the published statistical data. Li and Yang (2007) revealed the change of area of farmland in Anji County. Table 3.2 below includes values from both sources. Farmlands include paddy field and other fields, but paddy field is the dominant type of farmlands in Anji County, as the percentage row in the table demonstrates. Comparison of classified images indicates that the total areas of paddy rice fields did not change much between those years, so the 2000 land use data was selected to represent the county. However, the distribution of paddy field in the Anji County could affect experiments of spatial interpolation, which will be discussed.

Table 3.2 Statistics of Farmland in Anji County

| Year | Farmland | Paddy field (Based on Images) | Percentage (Paddy Field/Farmland) |
|---|---|---|---|
| 1991 | 220 $km^2$ | 199 $km^2$ | 90.4 |
| 1995 | 208 $km^2$ | 194 $km^2$ | 91.3 |
| 2000 | 210 $km^2$ | 193 $km^2$ | 91.9 |

### 3.2.4 Climate Data

The DNDC model requires daily maximum temperature, minimum temperature and precipitation records for each site. Daily weather data from 670 stations across China were provided by Dr. Zhang Feng at Lanzhou University in China. In this dataset, temperature and precipitation data were recorded continually from 1991 to 2009. Station weather datasets were interpolated to cover the whole country. For temperature data, a geostatistic technique, namely kriging, was adopted to do spatial interpolation. The semi-variogram model used is a spherical model, which defines the behavior of weather data variation as distance from the weather station increases. Inverse Distance Weighted (IDW) model was selected to interpolate precipitation data. All those interpolation were completed using geoprocessing functions provided by the ArcGIS 9.3 software package. Parameters were automatically calculated by ArcGIS based on the input datasets. Interpolation and validations were conducted in Lanzhou University and raster format data was received.

Additional data processing was required to make climate data useable for the DNDC model. A square area, which is larger than the actual shape of Anji County, was clipped from the national climate map. Then daily climate data for Anji County was selected from the clipped data using the resample and zonal statistics functions provided by ArcGIS. In ArcGIS, the zonal statistics function needs a shapefile, which is format used by ArcGIS to store digital maps, to define zones to do statistics. For this research, 18 Thiessen polygons were created based on the locations of the 18 selected villages. Each Thiessen polygon is a statistical zone used to calculate mean daily maximum/minimum temperature and precipitation in that zone. As a result, areas within one polygon (Fig. 3.6) will receive the same climate data.

Fig. 3.6 Zones Divided by Thiessen Polygons

# CHAPTER 4 METHODS AND RESEARCH DESIGN

## 4.1 MODEL SIMULATION AT SITE SCALE

The DNDC model has two options for crop growth simulation: regional model and site model. The regional model was designed for large area estimation, such as a province. This method assumes each spatial unit has the same farming practices and it requires only fertilizer usage as crop management input data. The disadvantage of the regional option is that it uses default farming practices instead of user specific crop management parameters. This reduces the flexibility for users to adjust the model and fit it to specific sites. For this study, detailed farming practice will be utilized to tell the difference between villages, so the site option was selected to simulate paddy rice systems in Anji County. Basically, this study designed two scenarios: site scale simulation with historical climate data, and site scale simulation with sole climate data.

### 4.1.1 Site Model I - Simulation with Historical Climate Data

The final input files for the DNDC model include a text format file, which includes crop management parameters and soil properties, and a climate file, which contains daily temperature and precipitation data. The time span of this research is 1991 to 2009. Continuous farming practice datasets were not available in the study area. Instead, the survey collected estimated farming practice data for years 1991, 1995, 2000, 2005 and 2009, as mentioned before. It is not appropriate to interpolate the farming practice data because some parameters are non-linear values. For example, it is hard to interpolate the planting and harvest dates. Thus years without survey data were simply assigned the same value of the most recent year with survey data. As a result, 20 years were separated into five groups and each group is based on one set of farming practice data. Details have been listed in Table 4.1.

Table 4.1 Farming Management Data Groups

| Group ID | Year with Survey Data | Group of Recent Years | Climate Files | Members in the Group |
|---|---|---|---|---|
| 1 | 1991 | 1991 to 1993 | 1991 to 1993 | 3 |
| 2 | 1995 | 1994 to 1997 | 1994 to 1997 | 5 |
| 3 | 2000 | 1998 to 2002 | 1998 to 2002 | 5 |
| 4 | 2005 | 2003 to 2007 | 2003 to 2007 | 5 |
| 5 | 2010 | 2008 to 2009 | 2008 to 2009 | 2 |

Under this scenario, every village will have 5 different farming practice input files for the last two decades. Climate files are different for each year. The two input files will provide ecological, soil and environmental drivers to drive the crop and soil biochemistry sub-models of the DNDC model. The model will then integrate all processes to simulate C and N circulation of paddy rice system at site scale for each village from 1991 to 2009, and simulate the crop growth and environmental impacts of paddy rice systems.

**4.1.2 Site Model II - Simulation with Sole Climate Data**

In model II, only one climate file for 2005, and five years with surveyed farming practice data (1991, 1995, 2000, 2005 and 2009) will be simulated. This is because this study has only 5 different farming management files, so it is meaningless to run the model with the same farming file and climate file multiple times. The purpose for this scenario is to separate the impacts brought by changes of farming practice from those brought about by climate change. Precipitation and temperatures for a certain area could vary greatly between years, and this could conceal the impacts brought by change of farming practice, such as an increase of fertilizer usage in the county. Thus, only one year – 2005 -- was selected as the climate input file to highlight the impacts of crop managements, because this will remove the effects of variation of climate data from the modeling results. In summary, 5 different farming practice files but with the same climate conditions, will be used by the DNDC model to identify the change of N fertilizer efficiency and N loss caused by change of farming practice, focusing on fertilizer usage. The process is similar to what was described in experiment I. Two files – farming practice file and climate file – will be employed as input data for the DNDC model and then the model will run crop and other sub models to calculate the C and N circulation of paddy rice systems. Table 4.2 listed the pairs of farming practice file and climate file used for each simulation.

Table 4.2 Pairs of Farming Practice and Climate File

| ID | Year of Farming Practice | Year of Climate File |
|---|---|---|
| 1 | 1991 | 2005 |
| 2 | 1995 | 2005 |
| 3 | 2000 | 2005 |
| 4 | 2005 | 2005 |
| 5 | 2010 | 2005 |

## 4.2 COMPARISON OF SPATIAL INTERPOLATION APPROACHES

### 4.2.1 Methods Discussion

Although it is good to have a detailed simulation for selected sites, as the two model scenarios designed, people may still need estimations for a region at the county level or above. In this case, there is a need to bridge site modeling with regional estimation. In other words, it is necessary to convert between point data and area data. Running the model on a large number of sites in a region might be an approximate solution, but usually it is not practical to do this. Alternatively, this study tried to interpolate data obtained at the village level to depict the big picture for a county. There are many potential approaches to do this, and the problem of spatial uncertainty will arise. Hence three experiments were designed to assess the sensitivity of modeling results to different spatial interpolate approaches. 2005 is the year selected to be the climate file for experiments. The land use data has not been used yet in previous experiments because they were just site based simulations. But in this part, land use data will be an important component. Specifically, the distribution of paddy field will affect the weighting factor for a certain soil type, which will be discussed in detail. The 18 Thiessen polygons created for climate data process will be used again here to define sub study areas (Fig. 3.6)

In this section, the diversity of soil properties plays an important role as input for the DNDC simulation. This is because within each polygon, the farming practice would be same, and the climate file would be the same too. Thus the variance of nitrogen fertilizer performance within the same polygon is mainly associated to the diversity of soil types. The purpose of this section is to explore the impacts of this diversity on nitrogen loss evaluation. A possible approach could be summarizing the number of soil types within each zone, as illustrated by the Fig 4.1, then pick up zones based on soil types. But this method does not utilize land use data. Alternatively, it is possible to summarize the area of paddy field within each soil type, as Fig. 4.2 illustrated. In this way, researchers could take advantages of both soil diversity and paddy field distribution.

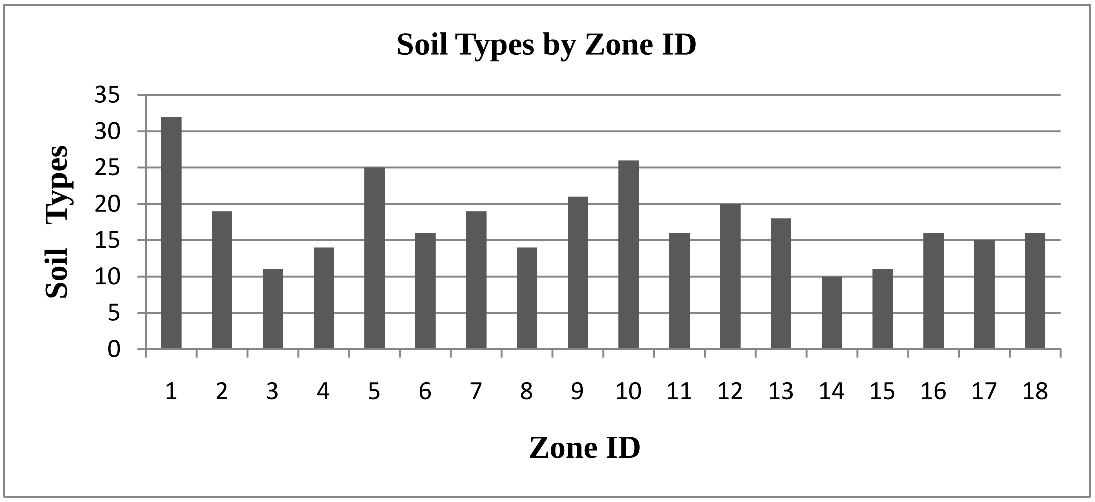



Fig. 4.1 Soil Types by Zone ID

The example given below selected zone 12, which is one of the 18 zones divided by Thiessen polygons, as an object. There are 20 types of soils in the zone, but not all soil types are equally important to paddy rice systems because only a few soil types are suitable for paddy field. In Fig. 4.2, readers can find that paddy field is concentrated in a few soil types. For this reason, a better approach would be weighting the impacts of different soil types on modeling results. Assigning a weight factor to different soil types could be achieved in many ways, and an easy method could be using the area of each soil type as the weight factor directly. This might reflect the spatial structure of soils in the polygon, since it sounds straightforward to give larger soil patches bigger weights; but this method can not reflect impacts of paddy field distribution. In fact, a patch with smaller area but more paddy field can be more important than a larger patch with less paddy field, as the Fig. 4.2 displays. Thus it is necessary to summarize the area of the paddy field in each soil patch first and then assign weights to the different soil types.

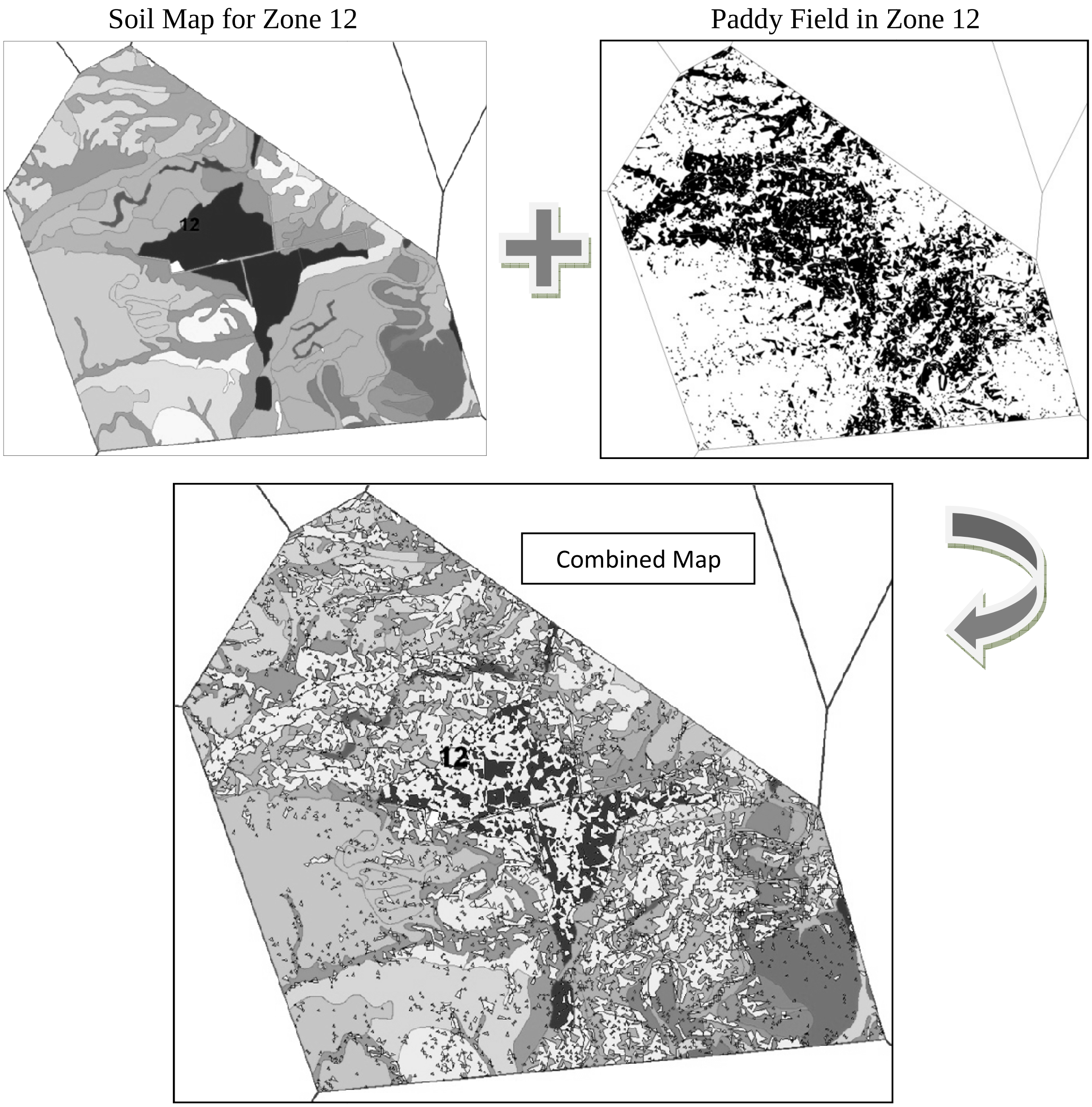


Fig. 4.2 Soil Patches and Paddy Field

After exploring the area weighted soil diversities for all 18 zones, three zones were selected to participate in further experiments, namely Zone 3, Zone 12 and Zone 16. Fig. 4.3 displays the distribution of paddy field by soil type in each zone. In the figure, the X axis represents the soil code used by the soil database and Zone ID is the identity number for the 18 zones. These three zones have different distribution patterns of paddy field. Zone 3 (ID=3) has only 11 soil types, and the paddy field is distributing relatively evenly among soil types. Zone 12 and Zone 16 have more soil types than Zone 3, and they possess a more concentrated pattern. These polygons will be used to do experiments next. Preprocess for each polygon is similar to that described in the Zone 12 example: layers of soil properties, paddy field, and village location will be overlaid in the ArcGIS software. Within the same polygon, all fields share one set of farming practice data. Soil properties include soil organic content, soil texture (clay and sand fraction), soil pH value, soil porosity, wilting point, field capacity, bulk density and hydro-conductivity.

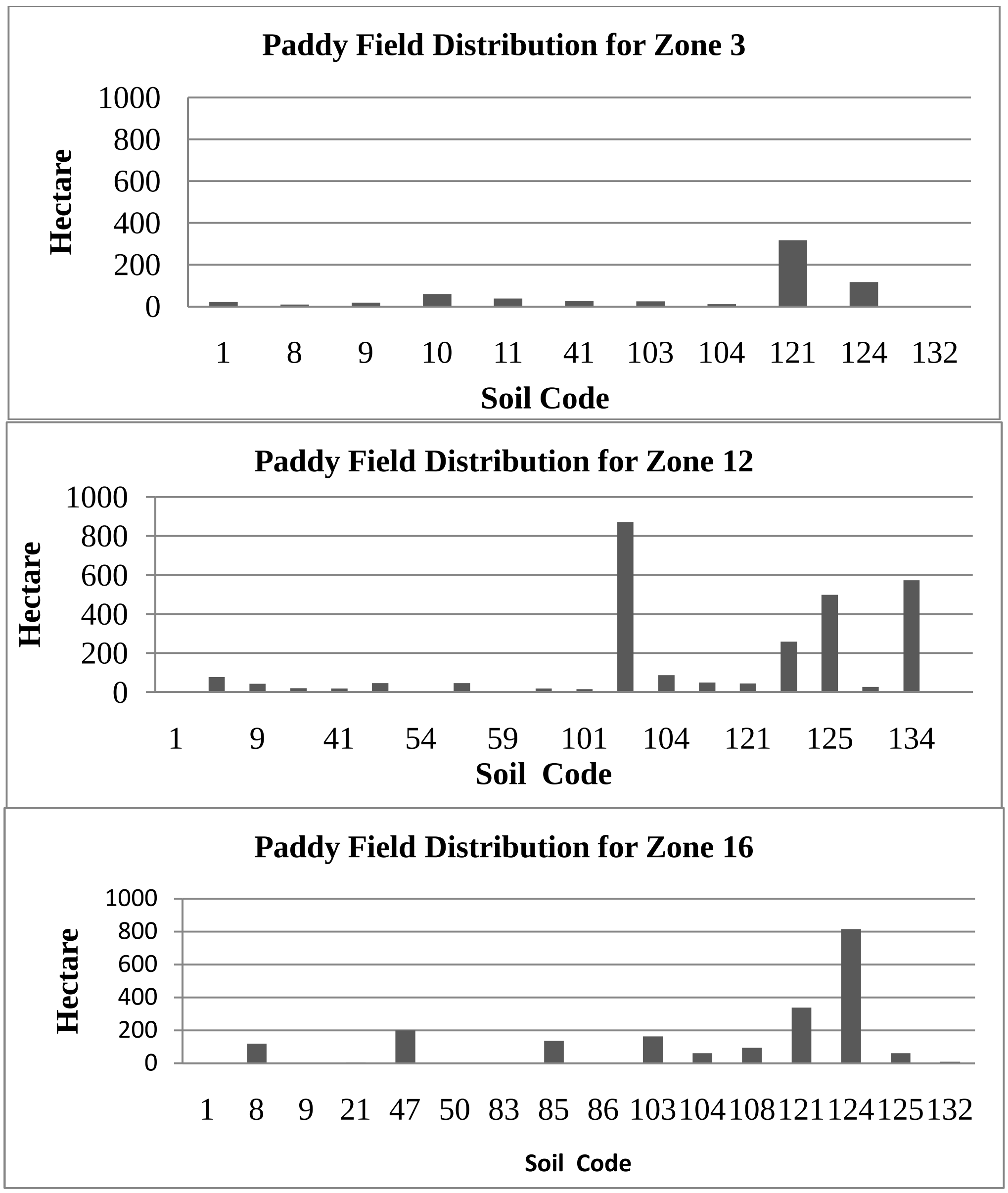


Fig. 4.3 Paddy Rice Field Distribution Based on Soil Types

### 4.2.2 Experimental Design

**Experiment A**

All three experiments ran the DNDC model for each of the selected 3 zones for year 2000, as mentioned before. Each zone has one of the 18 sites, and that site will be used to stand for the zone in experiment A. In other words, rates obtained from site-based modeling within a certain polygon will be used as the standard unit rate for that polygon. Then values for the region were calculated by multiplying rates with area of paddy field in the polygon. For example, in polygon A, the formula to calculate N loss for the polygon would be:

Total Nitrogen loss = TN (Kg N)

Unit rates of nitrogen loss from Site A (Kg N/ha) = UT (Kg N/ha)

Total area of paddy field in polygon A = TA = (Ha)

TN= UT * TA

**Experiment B**

In Fig. 4.3, it is apparent that many different soil types can exist even within the same zone, but experiment A takes only one soil type since it using the rate obtained from site- based modeling directly. This is a deficiency of experiment A. To improve this, experiment B will include the diversity of soil types by using area weighted soil properties instead of simply using the soil type contained in the specific site. By area weighted soil properties, it means the influences of different soils on the final averaged soil properties depend on the area of paddy field within each soil type. In other words, the more paddy field contained in a soil type, the higher weight that soil type will receive. For instance, if loam in a zone contains 50% of the total paddy field, than that soil type will get a weight of 0.5. An example given below will clarify the process. For instance, if there are $n$ (n>=1) types of soil in a study zone, then the area weighted soil organic content would be calculated in this way:

$$\mathbf{S}\text{avg} = \sum_{i=1}^{n}(Ai * Si) / At \,;$$

Where **S**avg = Area weighted SOC (soil organic content, kg C/ kg);

$\mathbf{A}_i$ = Area of paddy field within polygons of soil type i (ha);

$\mathbf{A}_t$ = Total Area of paddy field in a study zone (ha);

$\mathbf{S}_i$ = SOC of soil type A (kg C/kg).

Other soil properties will be calculated in the same way, and the new soil input file for each zone will then be simulated using the DNDC model again to check for any significant differences between experiments A and B.

**Experiment C**

This experiment did not try to average soil properties before running the DNDC model. Similar with to experiment B, experiment C will select only soil types with paddy field, but it will run the DNDC model on every soil type that contains paddy field within the same zone. Then, area of paddy rice fields were summarized based on soil types, which will be used as weight factor to scale modeling results based on each soil type. For example, if there are n (n>=1) types of soil within a study zone, then the formulation for $N_2O$ emission calculation will be:

$$\mathbf{N}\text{avg} = \sum_{i=1}^{n}(Ai * Ni) / At \,;$$

Where **N**avg = Area weighted average emissions of $N_2O$ (kg N);

$\mathbf{A}_i$ = Area of paddy field located in polygons of soil type i (ha);

$\mathbf{A}_t$ = Total Area of paddy field in a study zone (ha);

$\mathbf{N}_i$ = $N_2O$ emission based on soil type i.

Both experiments B and C utilized the diversity of soil properties and paddy field distribution within each study zone, but the methods are different. For experiment B, soil properties were averaged using the area weighted method and only one input file containing soil properties was used. In contrast, experiment C ran the model on each soil type that contained paddy field. Instead of averaging soil properties before modeling, experiment C prefers to average modeling results using area of paddy field as the weight factor. In this way, modeling results come from soil types with larger paddy field will have higher weight on the final estimation. The differences of modeling results between three experiments will be discussed later.

# CHAPTER 5 RESULTS AND DISCUSSION

## 5.1 SITE SCALE MODELING

In the last chapter, two approaches were adopted to simulate paddy rice systems in Anji County using the DNDC model. This chapter will discuss the modeling results, focusing on Carbon and Nitrogen balance of paddy rice systems.

### 5.1.1 Fertilizer Input and Nitrogen Deficiency

N Fertilizer has become the dominant external input source of nitrogen for paddy rice systems in China, while manure used to be the major fertilizer type. Major types of nitrogen fertilizer used in Anji County were compound and urea fertilizer. Generally, farmers in Anji County increased the amount of chemical N fertilizer applied in paddy field significantly, as displayed in Fig. 5.2, while manure input decreased after 2000 (Fig 5.1). Each line in Fig. 5.1 and 5.2 stands for one of the 18 selected villages, and the figures' legends included abbreviations of them. As the figures indicate, manure was almost completely replaced by nitrogen fertilizer after 2005. Fig. 5.2 displays that nitrogen fertilizer application increased quickly for most villages from 1995 to 2005, but the trend after 2005 is not clear. 5 villages decreased N fertilizer input since 2005, one village did not change at all, and all other villages increased their N fertilizer application. This is a diverse pattern and it is hard to predict what the pattern would be for next 5 or 10 years.

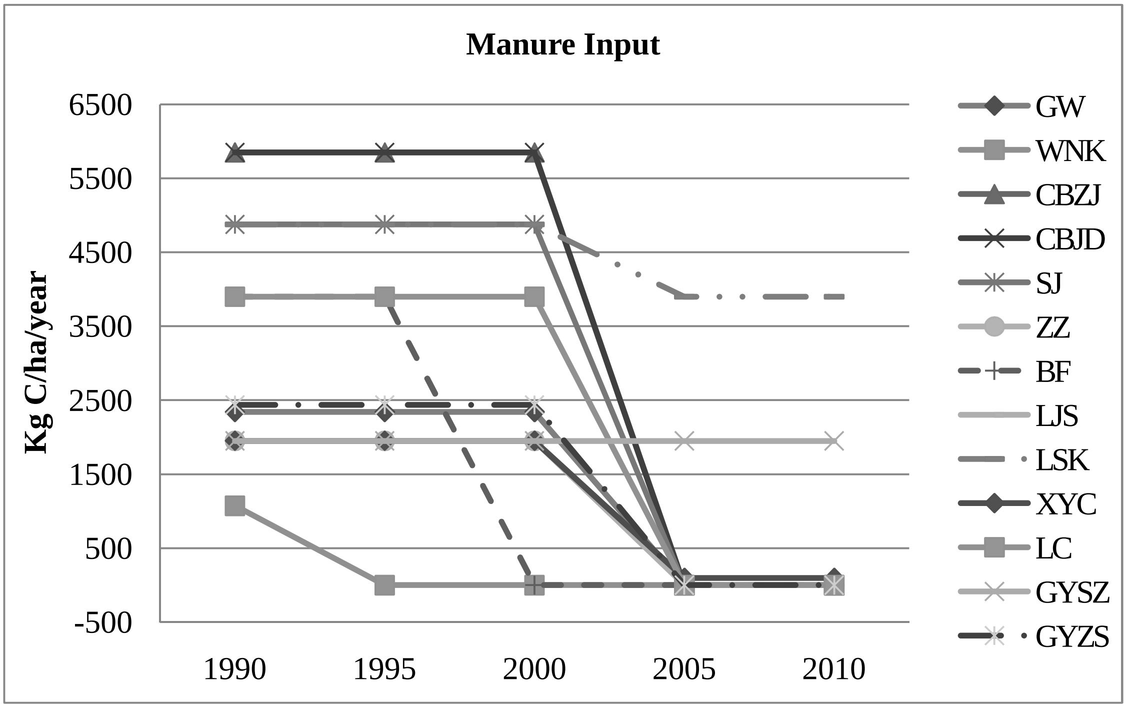



Fig. 5.1 Manure Input

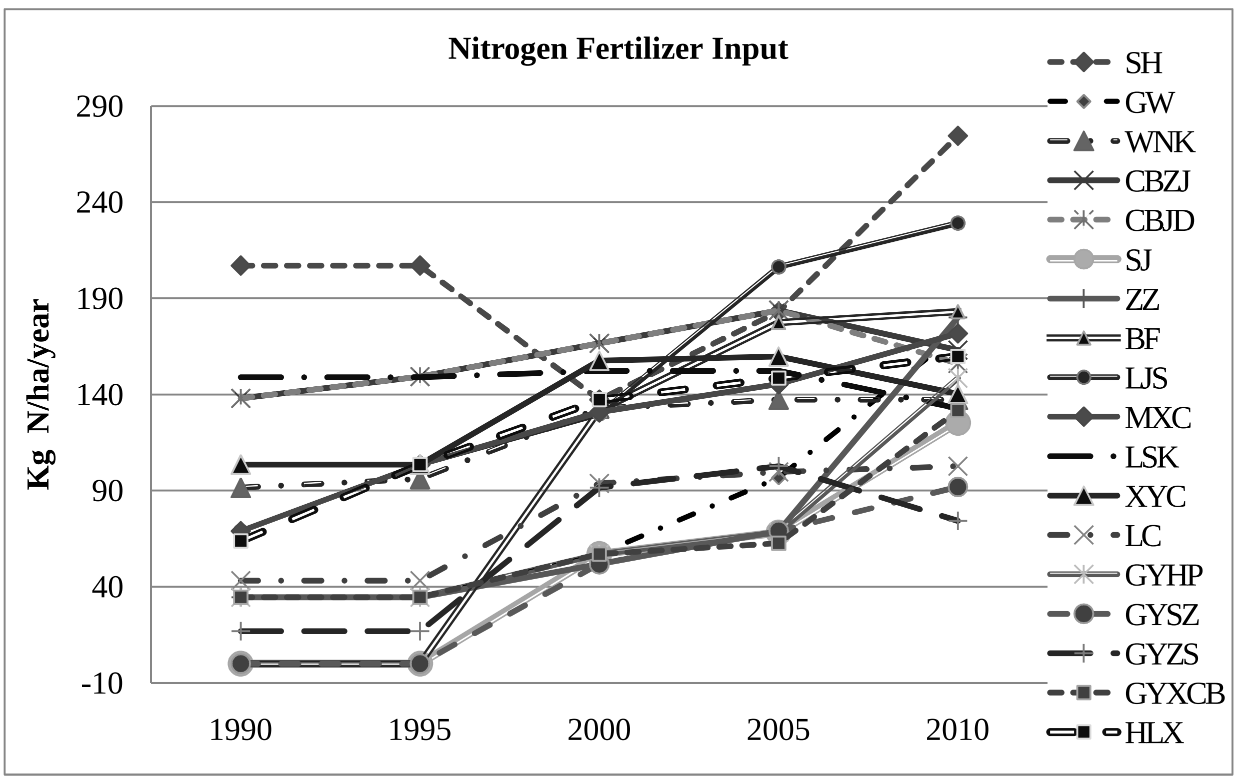



Fig. 5.2 Nitrogen Fertilizer Input

While farmers generally increased N fertilizer application, each five-year period during the last two decades has a different pattern. From 1990 to 1995, N application did not change much, but it increased quickly during the 1995-2000 period. Between 2000 and 2005, N fertilizer input was still increasing but at a slower rate. After 2005, fertilizer usage for different villages became more diverse. As stated before, there is no clear trend for all villages during this period. What caused the change of patterns for different periods? Changes in fertilizer price might be a reason. If the price is getting cheaper, farmers may tend to use more fertilizer because they think they can obtain more grain yields with the same budget through increasing N fertilizer input.

Fig. 5.3 displays changes in N fertilizer price between 1983 and 2005. The data source for Fig. 5.3 was organized by China.com.cn (2006) and the original data came from China Customs. FPI (Fertilizer Price Index) was employed to compare price change between years. It is assumed that the year prior to the starting year has an index equal to 100. Following years will be compared to that year to get an index. Formulas have been listed below:

Pa = Fertilizer Price of the year prior to the starting year

Pb = Fertilizer Price for the calculating year

PaI = Fertilizer Price Index for the starting year, which is 100.

PbI = Fertilizer Price Index for the calculating year

PbI = (Pb/Pa) * PaI or PbI = (Pb/Pa) * 100

Using this method, FPI was calculated from 1983 to 2005 only, since data beyond this time span was not publicly available. Nevertheless, it is helpful to explain why N fertilizer usage changed over the last couple of decades. Fig. 5.3 displays that FPI increased from 1990 to 1995 and then decreased from1995 to 2000.  This partly explains why farmers increased fertilizer usage quickly from 1995 to 2000 and were reluctant to do so between 1990 and1995.

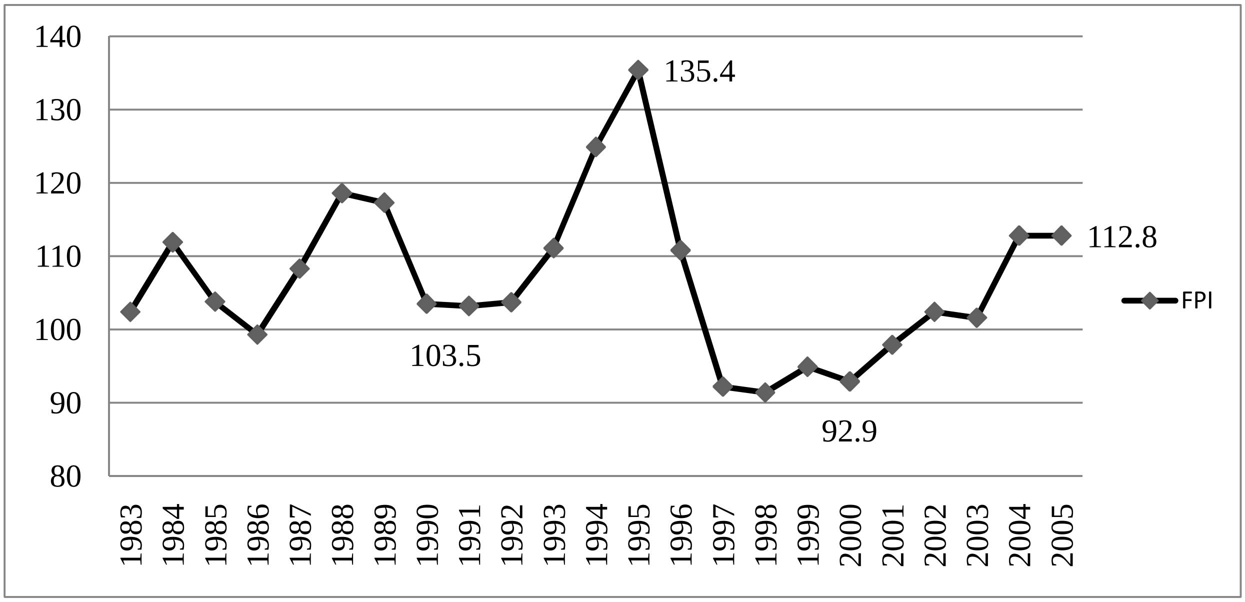



Fig. 5.3 Fertilizer Price Index

From 2000 to 2005, the price for fertilizers increased again, and rate of fertilizer usage slowed down correspondingly. Certainly there would be other factors influencing farmers' choice of fertilizer usage, but the FPI chart (Fig. 5.3) is a factor reflecting socio-economic impacts on fertilizer usage.

The next step is to assess the change of rice yields in Anji County for the last 20 years. It seems that farmers did increase application of nitrogen fertilizer considerably, but N demands of paddy rice systems, which have a positive correlation with grain yields, increased at the same time because rice yields increased gradually in China. Fig. 5.4 and 5.5 are simulated rice yields for Anji County between 1991 and 2009, generated by the DNDC model under two scenarios. In general, modeling results correspond with records of rice yields obtained through field surveys.

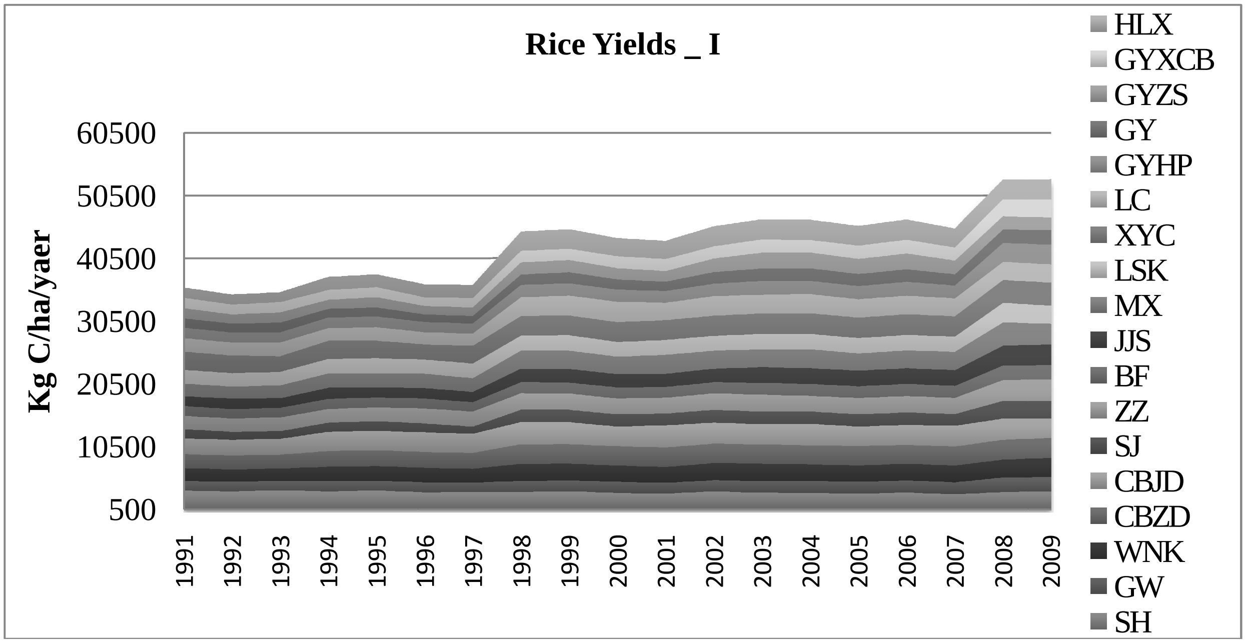



Fig. 5.4 Rice Yields from Site Model I (Kg C/ha/year)

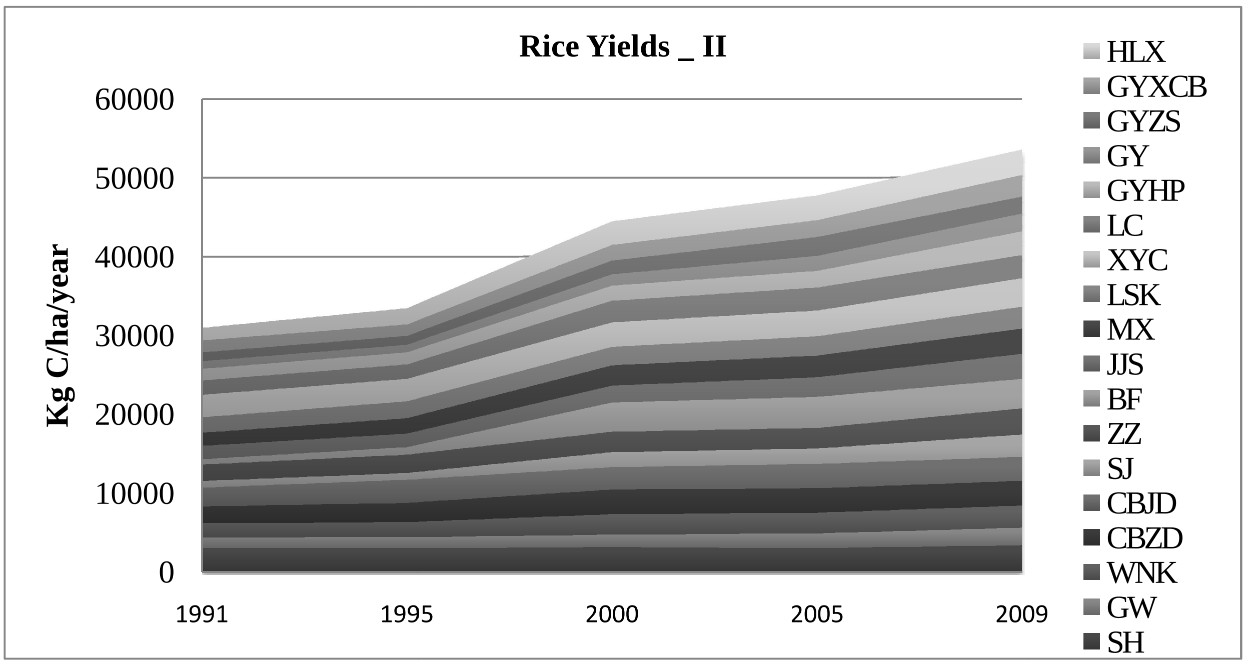



Fig. 5.5 Rice Yields from Site Mode II (Kg C/ha/year)

Details about Site Model I and II have been discussed in the methods chapter. For each village, Model I adopted historical climate data, which means each year's simulation received a unique climate file, while Site model II had only one climate file for the entire simulation. Both figure 5.4 and 5.5 indicate that rice yields increased gradually since the 1990s. The difference between two figures should be the results of variations in weather conditions between simulated years. The DNDC model will simulate daily growing conditions of paddy rice systems at each site. If the external conditions, such as precipitation, temperature, and fertilizer input cannot meet the requirements to achieve optimal grain yields, then the simulated grain yields will be lower than expected. As a result, there are fluctuations in the first diagram even between years that share the same set of farming management data.

So far, simulation scenarios indicate that both N input and N demands have increased gradually since the 1990s. Thus it is hard to tell whether N supplements were over applied or not without comparing them to N demands. Therefore, in this chapter, N supplements and N demands were put together to make a comparison. In general, N supplements could come from soil N storage and/or from external sources like fertilizer. In the DNDC model, N supplements include N from soil, N from air deposition and N fixation. If N supplements are insufficient, then there would be an N deficiency problem in the paddy field. Sometimes, crops can take more N nutrients from soils than the total N input because it is possible for crops to take some mineral nitrogen that initially existed in soil (Zhang et al. 2002). But this cannot last for a long time because soil fertility would decrease. Fig. 5.6 displays changes in N deficiency for Anji County between 1991 and 2009. N deficiency is the difference between crop N demand and the usable N taken by crops. The definition of N deficiency in this research can be formulated in the equation listed below:

**N deficiency** = Crop N demand **–** (Crop N from soil + Crop N from air $NH_3$ + Crop N fixation)

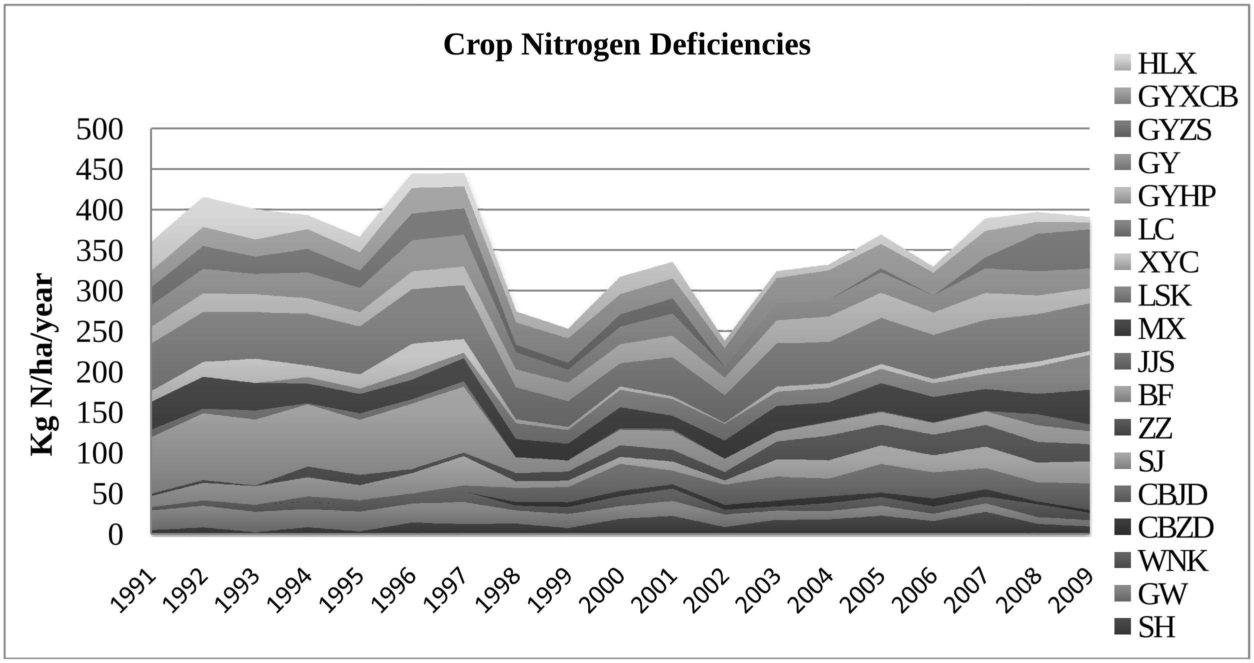


Fig. 5.6 Stack Figure of Crop Nitrogen Deficiency (Kg N/ha/year)

Layers in the diagram above (Fig. 5.6) are stacks of N deficiencies for 18 villages between 1991 and 2009. Each layer stands for the N deficiency of a certain village. The change of a layer's thickness represents the variation of N deficiency for a village between 1991 and 2009. Fluctuations in the diagram indicate that crop nitrogen deficiencies are different for the 18 selected villages at different years; some villages had small N deficiencies since their layers are very thin, while other villages in the same county had thick layers. This means excessive N fertilizer application is not a general practice for most villages. In fact, farmers in some villages should increase N supplements since there were noticeable N deficiency problems in their fields.

Noting that the difference between villages could be significant, it is necessary to assess the spatial variation of N efficiency before drawing a conclusion about whether farmers should uniformly reduce N fertilizer application. The overall trend of N deficiency for Anji County is not very clear, but roughly it seems that the N deficiency for the county decreased from 1991 to around 2000, and then increased gradually. However, this is only a comprehensive impression for the county. Further analysis indicates that the trends for all 18 villages can be categorized into four groups: A, B, C and D. The pattern for group A is that N deficiencies generally increased since the 1990s. In contrast, N deficiencies for villages in Group B decreased since the 1990s. The patterns for Group C and D are more complex: values in Group C decreased from 1991 to 2000 but increased after 2003; while N deficiencies in Group D increased from 1991 to 2007 but the values decreased quickly after that. The following four diagrams (Fig. 5.7, Fig. 5.8, Fig. 5.9, and Fig. 5.10) display that N deficiencies for different villages are vary even within the same county; not only are overall trends different between groups, but also the differences between villages are not consistent over time. As the figures display, each group has a unique overall trend, and the differences between villages are dynamic as well in all groups. This suggested that it might not be appropriate to discuss N fertilizer usage at the county level. Instead, it is necessary to carry out further analysis at village level.

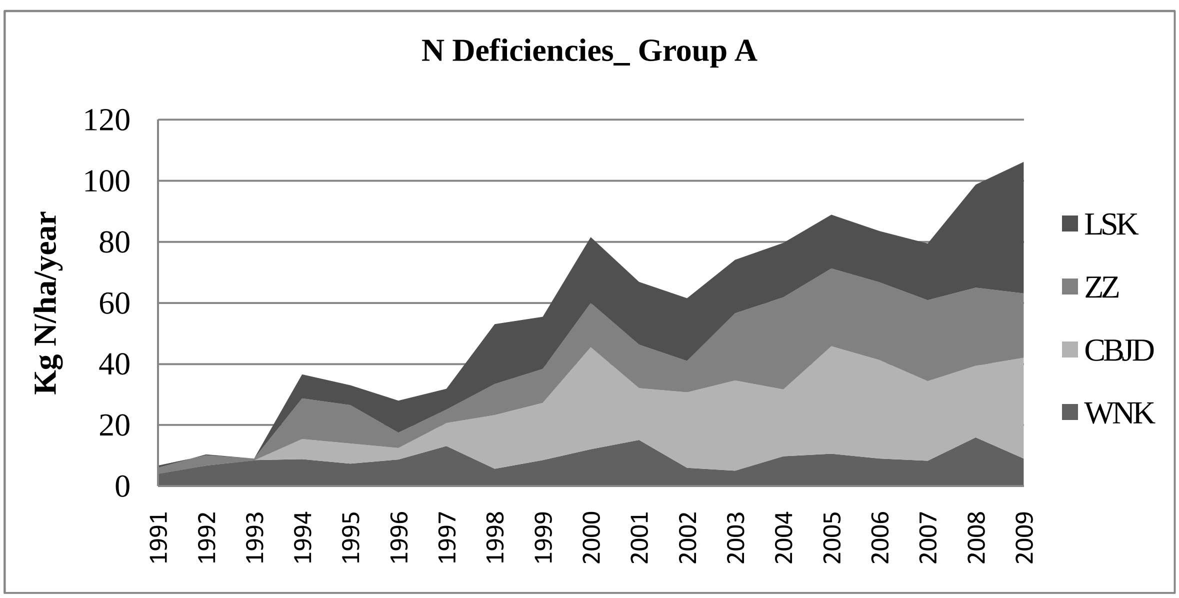


Fig. 5.7 Stack Figure of N Deficiencies for Group A (Kg N/ha/year)

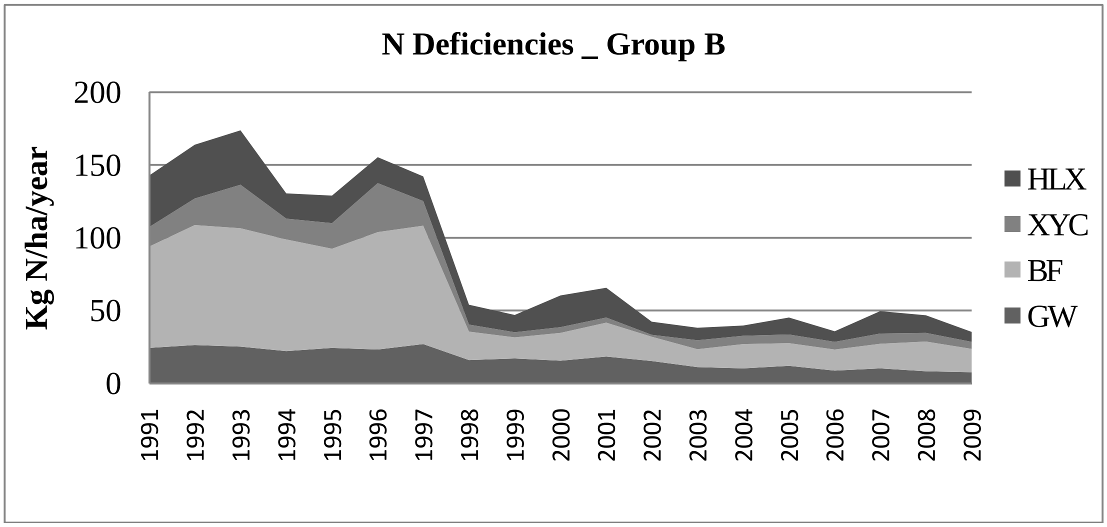



Fig. 5.8 Stack Figure of N Deficiencies for Group B (Kg N/ha/year)

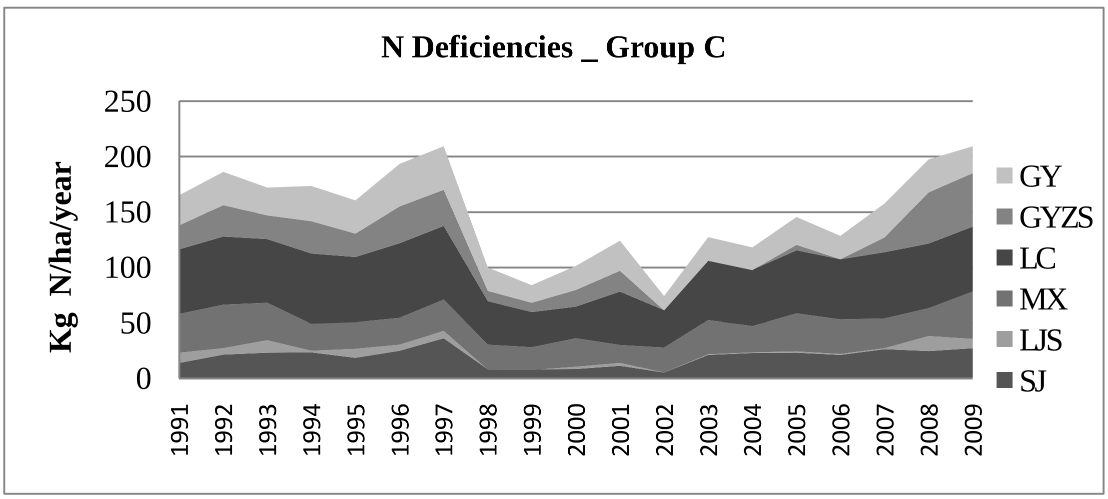



Fig. 5.9 Stack Figure of N Deficiencies for Group C (Kg N/ha/year)

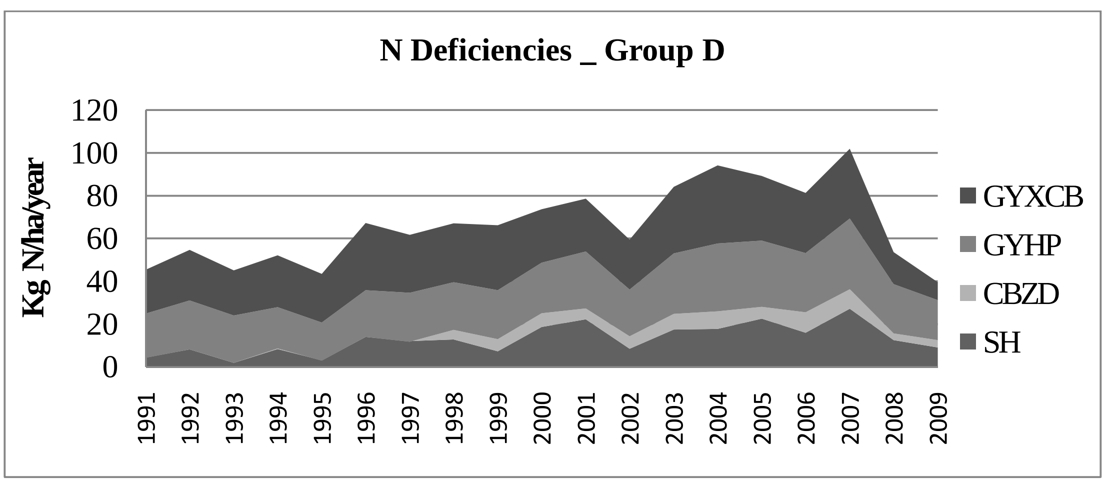



Fig. 5.10 Stack Figure of N Deficiencies for Group D (Kg N/ha/year)

## 5.1.2 Greenhouse Gas Emissions

Paddy rice fields will produce greenhouse gases, and the major types emitted from paddy rice systems are Methane ( $CH_4$), Carbon dioxide ($CO_2$), and Nitrous Oxide ($N_2O$ ) (Li 2005).

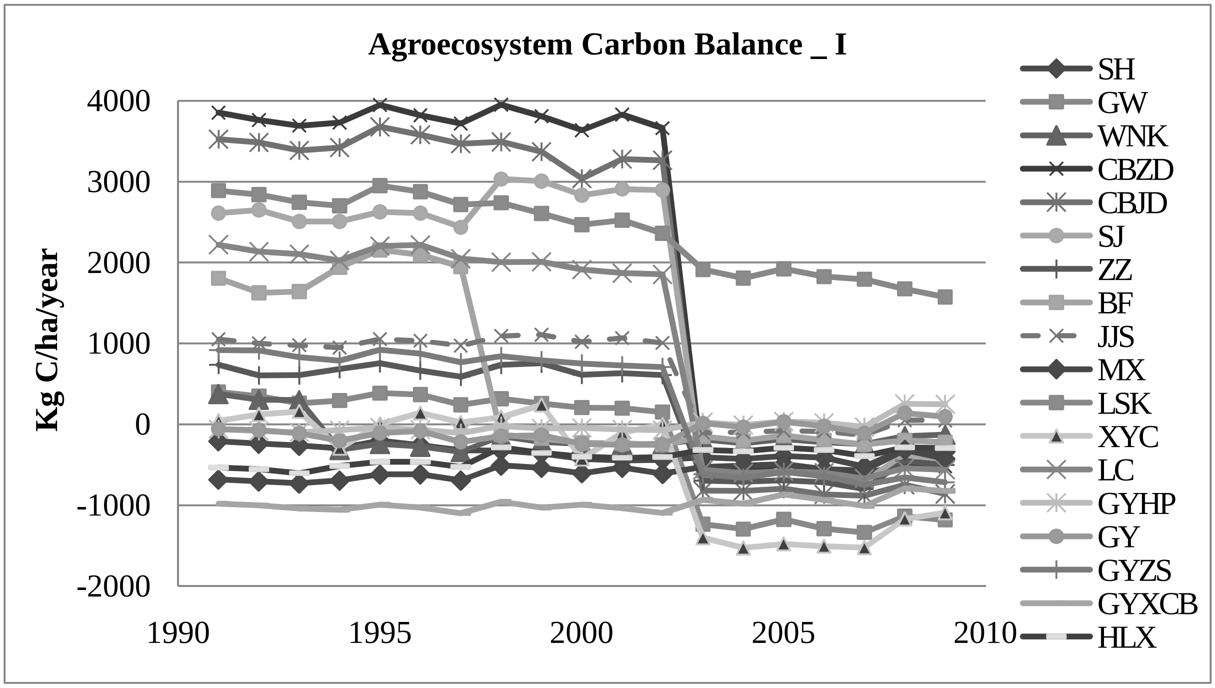



Fig. 5.11 Agroecosystem Carbon Balance for Site Mode I (Kg C/ha/year)

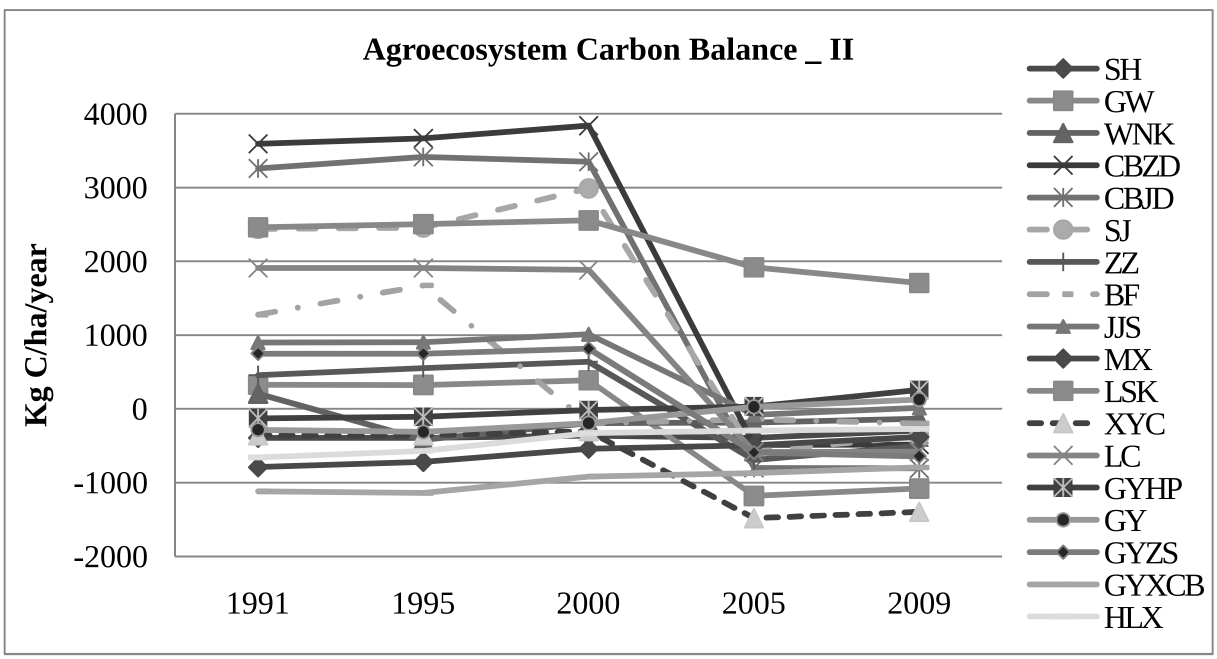



Fig. 5.12 Agroecosystem Carbon Balance for Site Mode II (Kg C/ha/year)

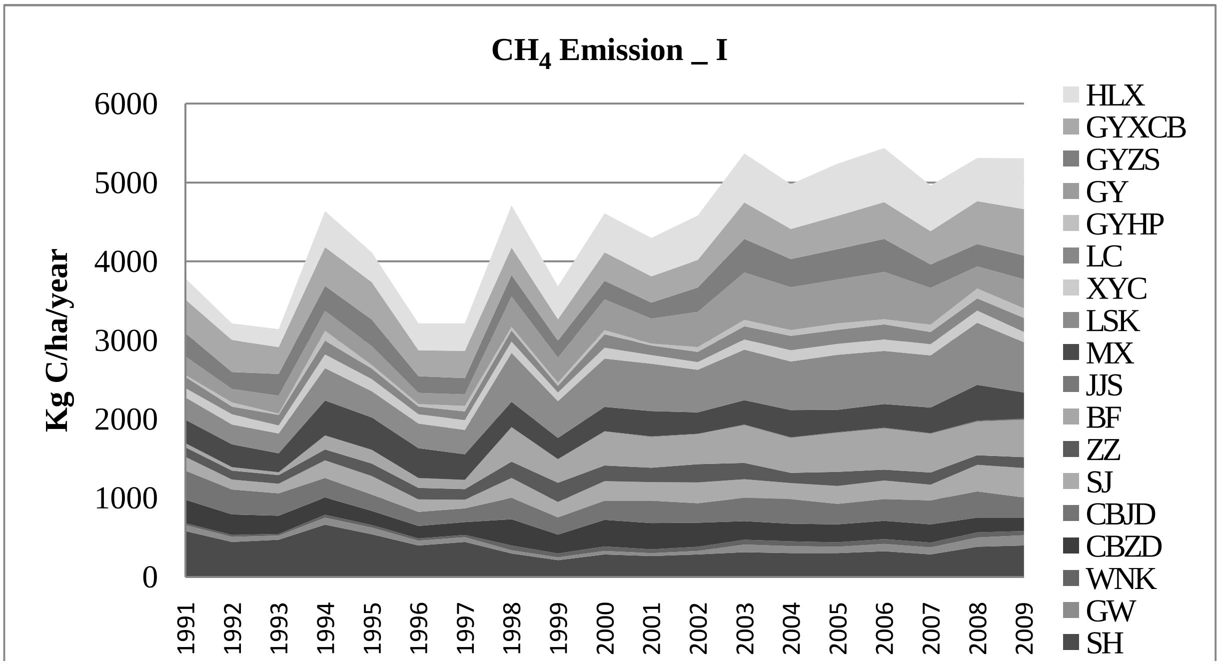



Fig. 5.13 Stack Figure of $CH_4$ Emissions from Site Mode I (Kg C/ha/year)

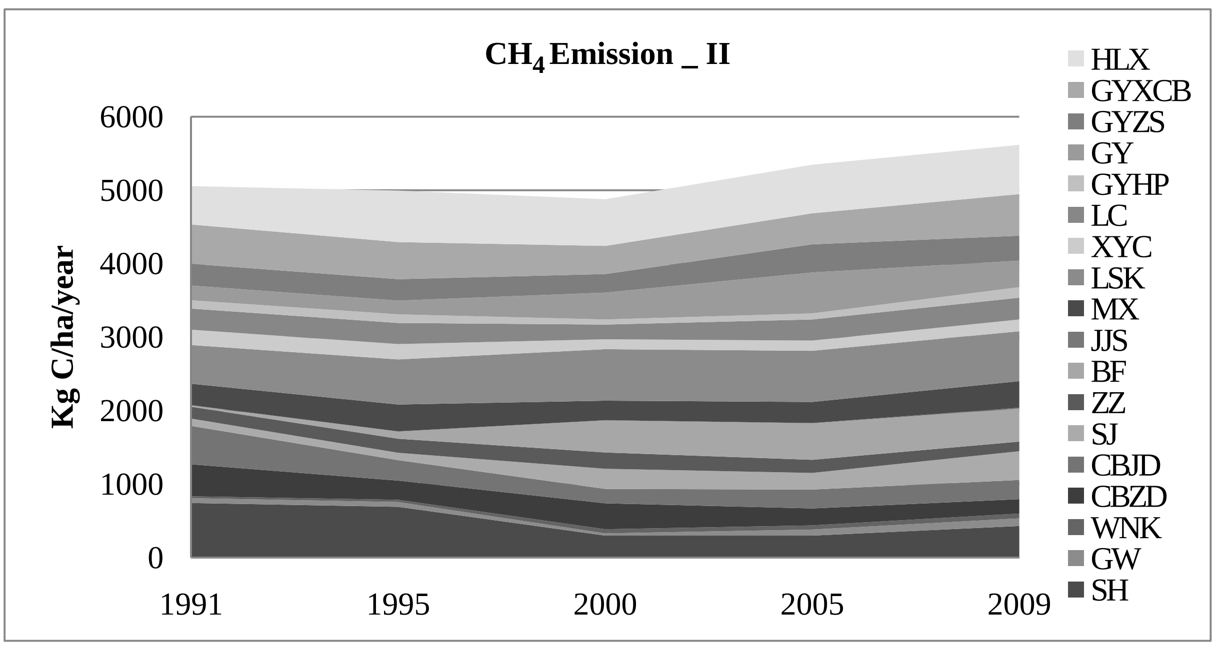



Fig. 5.14 Stack Figure of $CH_4$ Emissions from Site Mode II (Kg C/ha/year)

In the DNDC model, annual changes in SOC (soil organic content), $CH_4$ and $N_2O$ will be calculated to quantify net greenhouse gas emissions from agroecosystems. The developers of the DNDC model noted that changes of SOC have a negative correlation with a site's net $CO_2$ flux

(Li 2005). In fact, changes of SOC are an indicator of Carbon balance for agroecosystems. The positive values for Carbon balance change suggest the system received Carbon from external sources, which were the results of Carbon sequestration. In contrast, negative values indicate that the system lost Carbon to the environment, which escaped into the air mainly through $CO_2$ flux. The results of Carbon balance from Site Mode I and II share similar patterns. This indicates that changes in farming practice have stronger impacts than weather changes on Carbon balance in this case. The patterns of Carbon balance figures may be the results of manure usage changes, because manure will help paddy field to increase C storage. Carbon balances for 18 villages were positive before 2000, but Carbon balance became negative after 2005, which means paddy rice systems have been losing Carbon. This could cause soil degradation and also produce more $CO_2$ emissions. For $CH_4$ emission, Fig. 5.14 indicates that replacing manure with fertilizer had contributed to the increase of methane emission, since the climate conditions were the same for all simulated years under experiment II scenario. The difference between Fig. 5.13 and Fig. 5.14 is more noticeable than that for Carbon balance: there are more fluctuations in Fig. 5.13 than 5.14. This suggests that methane emissions are more sensitive to weather change than carbon balances.

Modeling results indicate that weather changes for the last 20 years had affected the patterns of greenhouse gas emissions, such as the $CH_4$ example discussed above and $N_2O$, which will be discussed next. Fig. 5.16 highlights the impacts of farming practices change on $N_2O$ emissions. In this diagram, it seems that $N_2O$ emissions decreased from 1991 to 2005 and then increased after 2005, and there are no noticeable waves. In comparison, the trends in Fig. 5.15 are much more dynamic: several peaks and bottoms in the figure make it be distinct from Fig. 5.16. This suggests that $N_2O$ emissions in the study area are sensitive to weather variations. In fact, changes of weather have more important impacts on $N_2O$ fluxes than fertilizer usage, since the changes in Fig. 5.15 are much more significant than those in the Fig. 5.16.

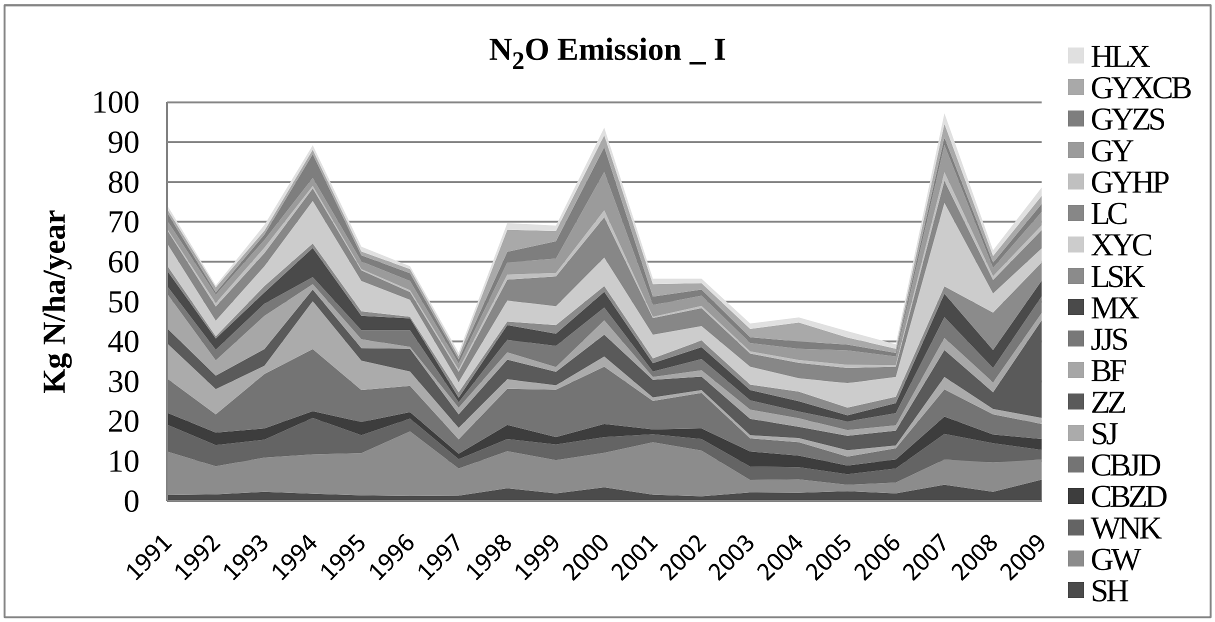



Fig. 5.15 Stack Figure of $N_2O$ Emissions (kg N/ha/year) - Site Model I

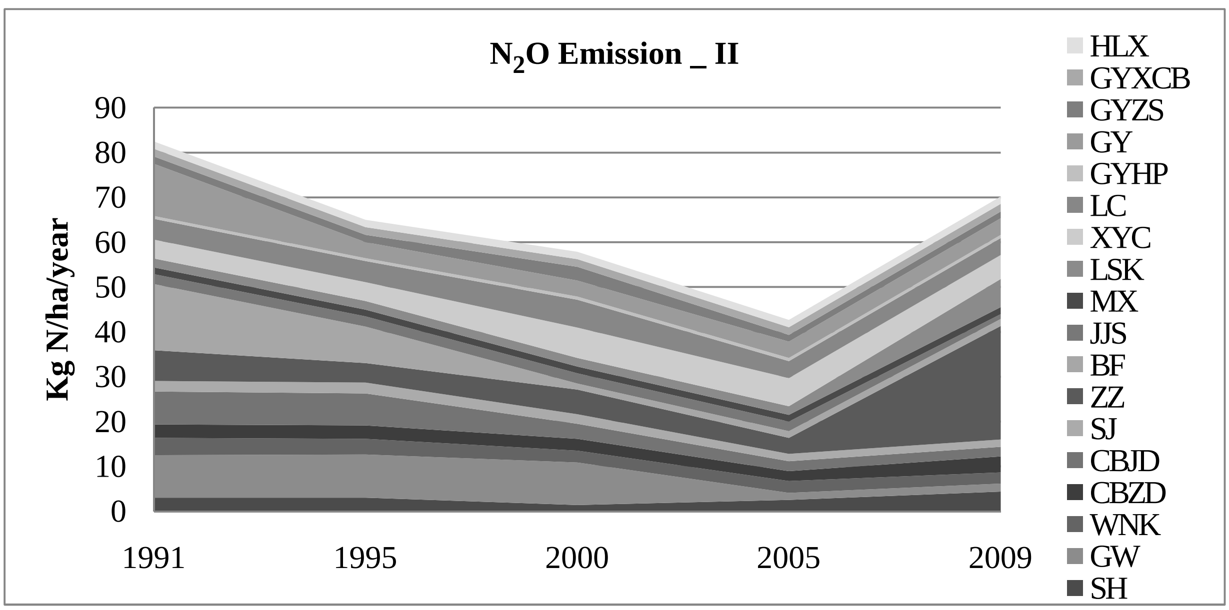



Fig. 5.16 Stack Figure of $N_2O$ Emissions (kg N/ha/year) - Site Model II

Both Fig. 5.15 and Fig. 5.16 indicate that the differences in values between villages were not constant between 1991 and 2009. This is more explicit in the Fig. 5.15, since the fluctuations were much more significant during that period. For instance, some villages, such as XYC village, are much more sensitive to weather change, while other villages have moderate variations, such as GW village. These results show that both spatial and temporal variation could bring significant fluctuations in regards to greenhouse gas emissions.

### 5.1.3 Nitrogen Leaching

Besides gaseous emission, unused nitrogen in paddy field could also be lost through nitrogen leaching. The topography pattern (Fig. 3.5) displays most paddy field is located in plain areas, which is helpful to reduce nitrogen loss through surface water runoff. Furthermore, ridges of fields usually will stop water runoff from paddy field, thus the N loss through runoff could be ignored. The results from simulated results also show that runoff N is zero. However, water leaking is unavoidable in paddy field due to the porous nature of the soil. As a result, water leached through soil pores will take away some N in soils.

The simulated results suggested that nitrogen leached from paddy field in the county decreased from 1991 to 2009, although N fertilizer application in this county experienced a considerable increase. This is beneficial to the environment: otherwise water pollution would be even worse, since lost N in surface water will contribute to water N pollution. Below, precipitation (Fig. 5.17) and N leaching (Fig. 5.18) figures were put together for comparison and it seems that these two components have a positive correlation: the waves and bottoms in both diagrams are similar in general. This indicates that precipitation has a strong influence on N leaching.

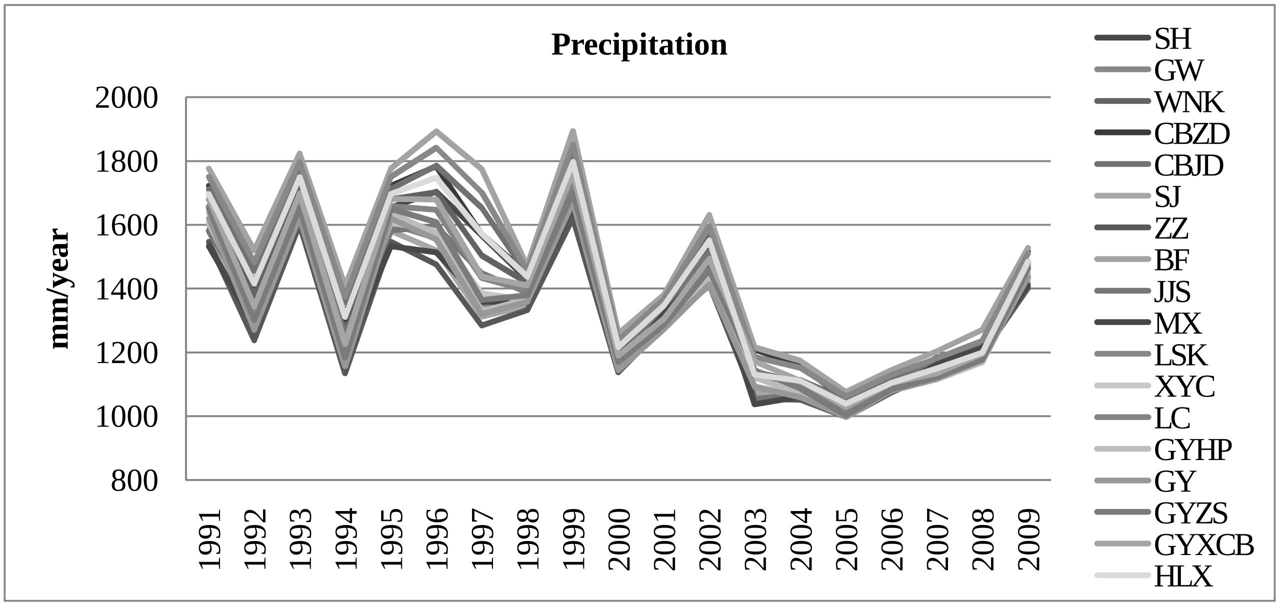


Fig. 5.17 Annual Precipitation (mm/year)

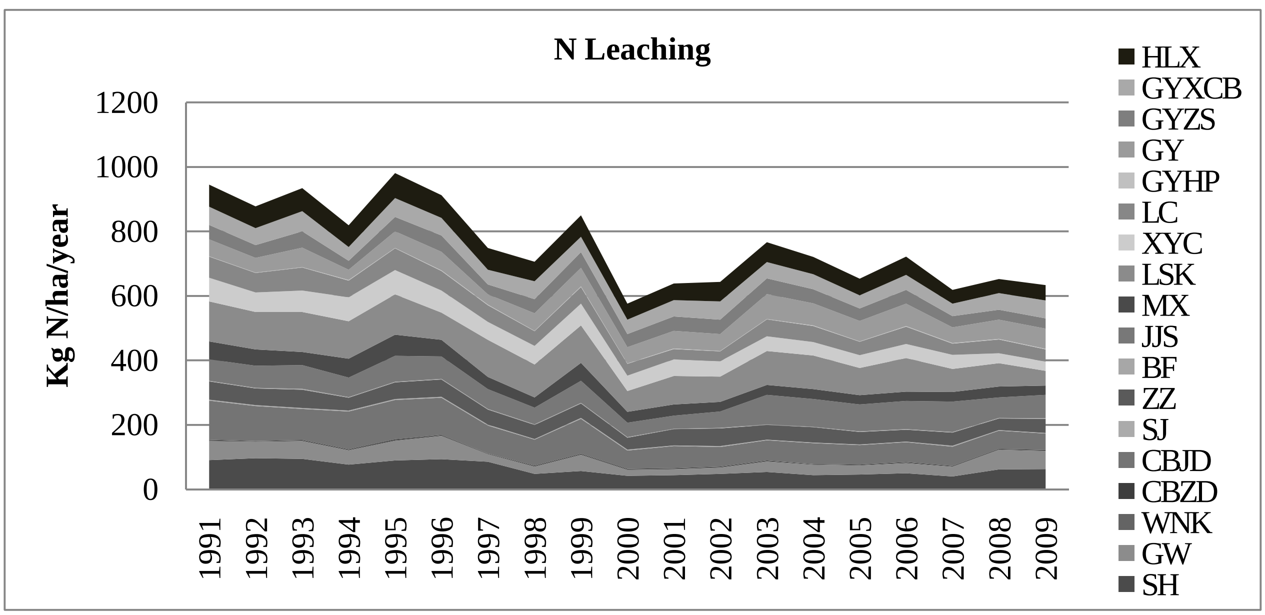


Fig. 5.18 Stack Figure of Nitrogen Leaching (kg N/ha/year)

### 5.1.4 Nitrogen Deficiency and Efficiency Discussion

So far, N deficiencies, N leaching and N input have been discussed individually. In this section, those three factors will be discussed together to better understand N usage in Anji

County. As stated before, this research shows that both spatial and temporal variation could bring significant fluctuations in regards to nitrogen waste and fertilizer use efficiency. To present these variations, two indicators were defined here: Index I and Index II. Formulas used to define these two indicators have been listed below:

**A**: N deficiencies (Kg N/ha/year)    **B**: N leaching (Kg N/ha/year)

**C**: N demand (Kg N/ha/year)

**D**: Total N input, including N fertilizer and manure (Kg N/ha/year)

**Index I** = A/C

**Index II**= B/D

Index I is a reflection of the severity of N deficiency for a study zone. Comparing N deficiency values directly cannot tell the difference of N stress between study zones very well, so N demand was employed to normalize N deficiency.

Index II is a good indicator of N efficiency: Lower values for Index II mean smaller portions of applied N were lost, while high values suggest more N in paddy field has been lost. Low N efficiency is not environmentally friendly because leached N will increase nitrate concentration in water bodies and then contribute to a series of environmental problems.

Fig. 5.19 displays the names of villages with their corresponding zone numbers, and Fig. 5.20 depicts the distribution of paddy rice fields in the county. Modeling results obtained from Site Model I will be used to generate maps for the county, using the 18 zones defined before as boundaries. For each of the 18 zones, Index I and II will be calculated and displayed below to reflect spatial variations of N deficiency and efficiency for the county over the last 20 years.

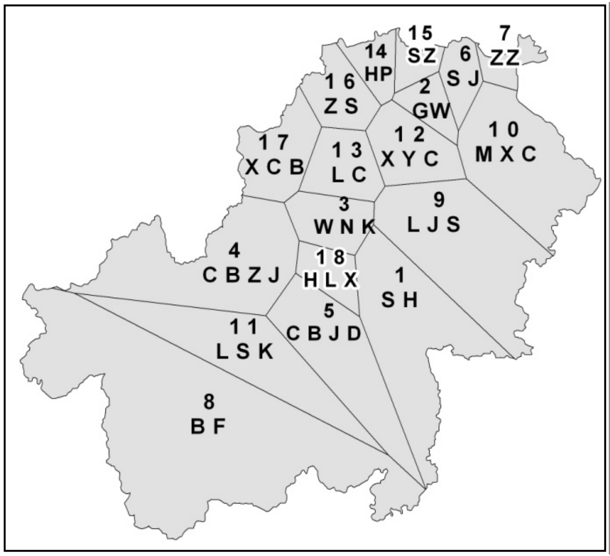



Fig. 5.19 Zone Number and Village Name

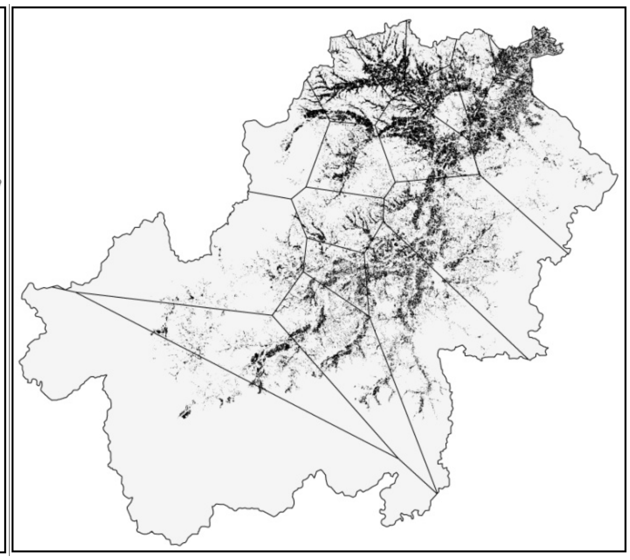


Fig. 5.20 Paddy Field and Zone Boundary

Fig. 5.21 displayed the dynamic patterns of N deficiency severity in Anji County between 1991 and 2009. It should be said that N deficiency severity for different zones varied significantly even within the same county. Generally, it seems that the N deficiency problem has been improved since the 1990s because the 2000s possess more zones with a light color, while they are several dark zones in 1990s figures. This might be because famers increased application of N fertilizer, which is more efficient than the manure which was a major fertilizer in the early 1990s. However, it is not true that the N deficiency problem has always been mitigated since the 1990s. In fact, 2000 and 2002 presented a better N balance than 2009 since N application at that time more closely matched crop needs. Furthermore, the difference in the N deficiency problem between zones is more noticeable in the early 1990s than in the early 2000s, but this difference has increased after 2005. This suggests that it is not true that most villages applied too much fertilizer in paddy field since the 1990s. In fact, some villages did not increase N application enough to keep up with growth of rice yields. As a result, there are dark gray zones in Fig. 5.21, and the color of zones changed dynamically from 1991 to 2009. This indicates that N deficiency problem for the county did vary significantly spatio-temporally, and it is important to understand the causes of these changes for different study zones before drawing any general conclusions for a large area.

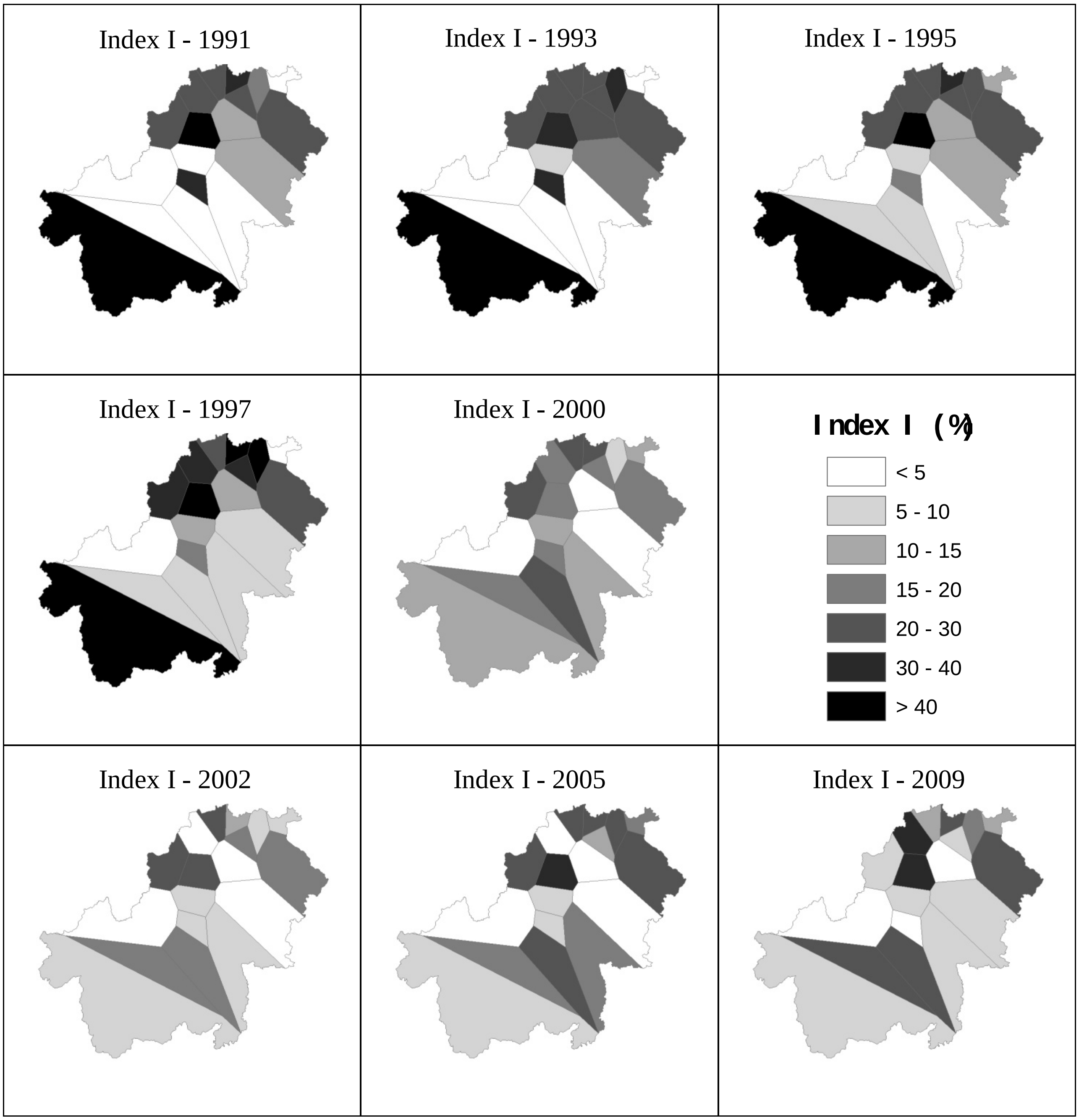



Fig. 5.21 Index I (%)

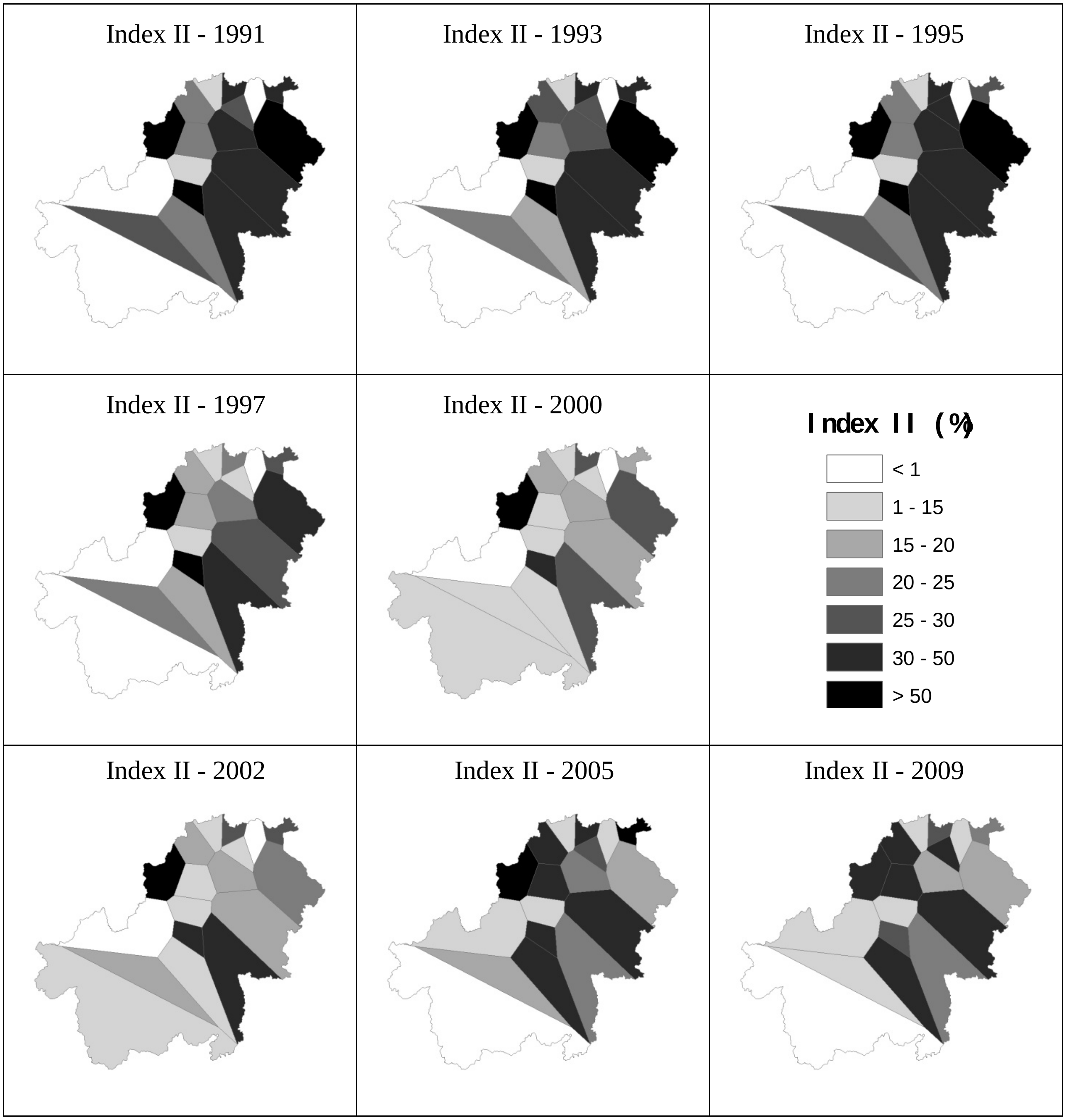



Fig. 5.22 Index II (%)

In general, dynamic changes in differences between zones in Fig. 5.22 are apparent. Geographically, it seems that zones in the North-East have higher values than zones in the South-West, especially in the early 1990s. This suggests that N efficiencies were generally lower in North-East zones. Possible causes of low N efficiency include soil properties, excessive fertilizer application and/or manure application. Some soil types have higher hydro-conductivity and they tend to leach more water from paddy field, which will cause N leaching at the same time. Some places might have high Index II values because they have more N in fields than needed and thus unused N lost through N leaching. In addition, manure is less efficient than chemical nitrogen fertilizer, so it will waste more N than N fertilizer. The low N efficiency for a specific study site may be caused by one or more factors mentioned here.

Index II values were generally lower around 2000 and 2002, which indicates that fertilizer application at that time was relatively more reasonable than other times. Although Index II values increased after 2002, the situation in 2009 is still roughly better than that in 1991 since most zones had lower Index II values and higher N efficiencies in 2009. Also, the distribution of high and low Index II values was more diverse in 2009 than in 1991. What these results suggest is that, even within the same county, N efficiencies did vary significantly spatio-temporally. Therefore, it is necessary to look into the causes of differences between villages.

### 5.1.5 Further Discussion with Selected Sites

As stated before, the 18 selected villages in Anji County can be categorized into 4 groups based on their N deficiency trends. For each group, one of the villages in that group was selected as the standard village. The four villages selected are LSK, HLX, LC and XCB. These villages will be examined more thoroughly to understand the changes in N usages and N efficiency between 1991 and 2009. Further analysis will help to identify individual agricultural improvement strategies for different groups, which is preferable to uniform policies. In the following discussion, N stress will be employed as one of the evaluation indicators. This factor is used in the DNDC model to evaluate whether crop growth has been suppressed by N deficiencies.

N stress ranges from 0 to 1. 1 means no N stress effects, while 0 means crop growth is completely limited (Zhang et al. 2002)

### 5.1.3.1 LSK

Overall, rice yields and N deficiency for LSK village increased since the 1990s (Fig. 5.24), and the rates of increase for both accelerated after 2007. Between 1991 and 2005, grain yields increased 12.4% (Fig. 5.23) , but N fertilizer application increased only 2.3%, so the N deficiencies for this village changed from negative values, where N input exceeded N uptake capacity, to around 20 kg N/ha per. In 2009, N deficiency for this village doubled from 2005, as rice yields increased nearly 25% while N input decreased about 13%.

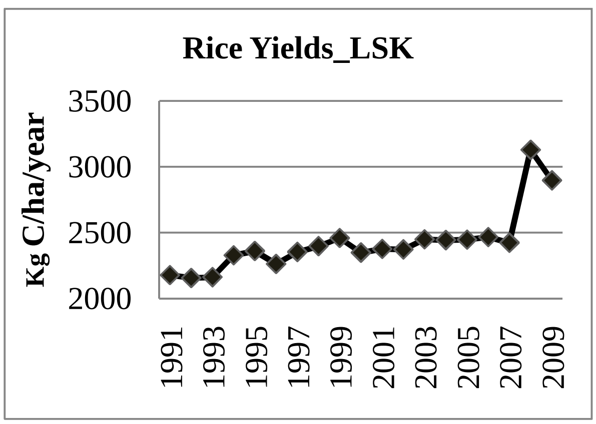



Fig. 5.23 Rice Yields for LSK Village

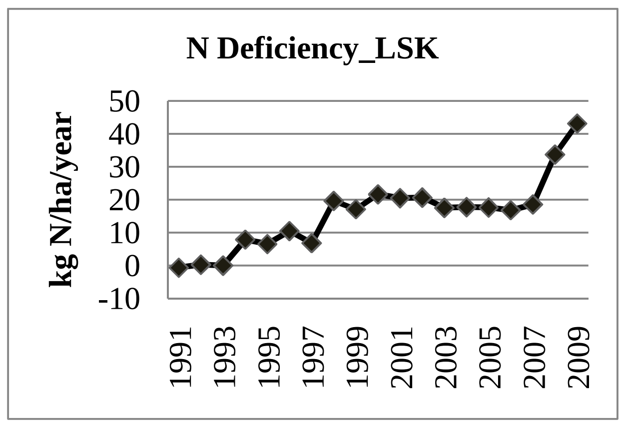



Fig. 5.24 N Deficiency for LSK Village

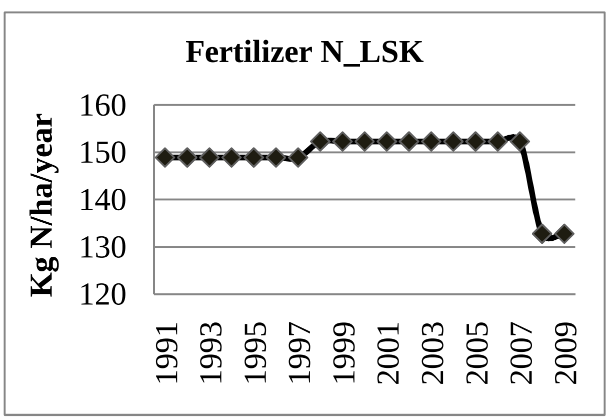



Fig. 5.25 Fertilizer N for LSK Village

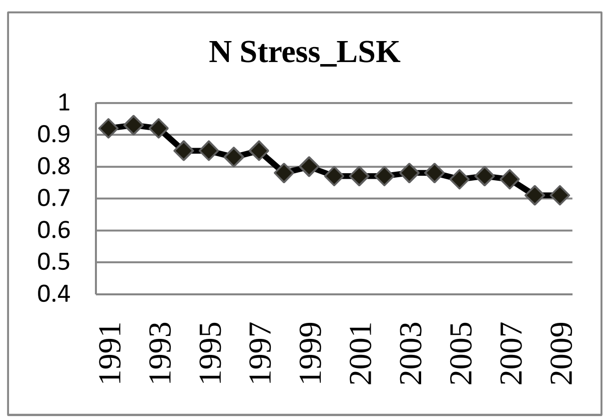



Fig. 5.26 N Stress for LSK Village (unitless)

The N stress (Fig. 5.26) diagram also indicates that farmers in this village should increase N storage in soils to make up the deficiency, rather than adopt any N limits. To test this hypothesis, experiments using the DNDC model were conducted. The X axis in all the following figures in this section measures how much more N fertilizer was added to paddy field than the amount used in 2009. The difference between the two lines is that the fertilizer in the dark line -- experiment 3 -- was applied 3 times while N in the light gray line --experiment2 – was applied 2 times, the same with the current practice. *Note that the total amount of N fertilizer input for both methods were the same*. GWP (Global Warming Potential) is a new variable to be discussed in this chapter. This variable is used to assess net effects of each modeling scenario on global warming. According to Li et al. (2006), the warming forces of $CH_4$ and $N_2O$ are 21 and 310 times higher, respectively, than that of $CO_2$. Thus GWP values for each simulated scenario were calculated as follows:

$GWP_i = CO_{2i} + N_2O_i * 310+CH_{4i} * 21;$

With

$CO_{2i} = C_i * (44/12)$

$N_2O_i = N_i * (44/28)$

$CH_{4i} = C_i*(16/12)$

In general, modeling results show that rice yields increased as N fertilizer application increased, but N leaching and greenhouse gas emissions increased at the same time. Furthermore, rice yields did not increase when N fertilizer application increased more than 50%, as Fig. 5.27 displays. After that, greenhouse gas emissions increase much faster than rice yields, as Fig. 5.29

and Fig. 5.30 display. These figures are double-Y diagrams and rice yields correspond to the right Y axis. Also, N fertilizer applied 3 times generally has better performance than a 2-time application; since dividing the fertilizer application into three occurrences got higher rice yields but lower greenhouse gas emissions (Fig. 5.28). However, N leaching is higher when N fertilizer was applied in 3 treatments, as Fig. 5.28 displays. One thing that needs to be mentioned is that the timing of the third application will affect rice yields and nitrogen loss, and thus the experiment here is just one of the possible results with a third N fertilizer application.

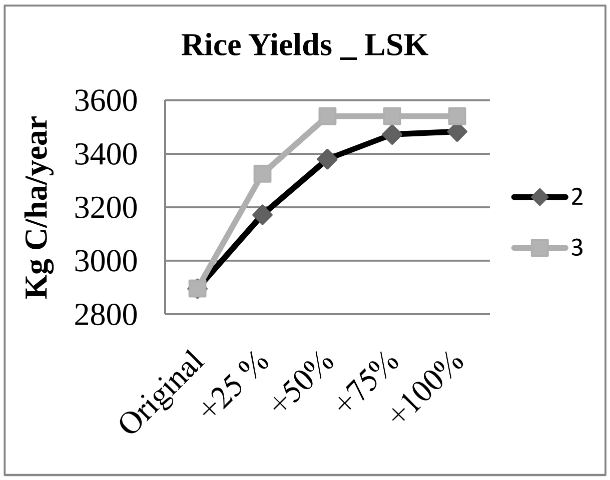



Fig. 5.27 Rice Yields for LSK Village

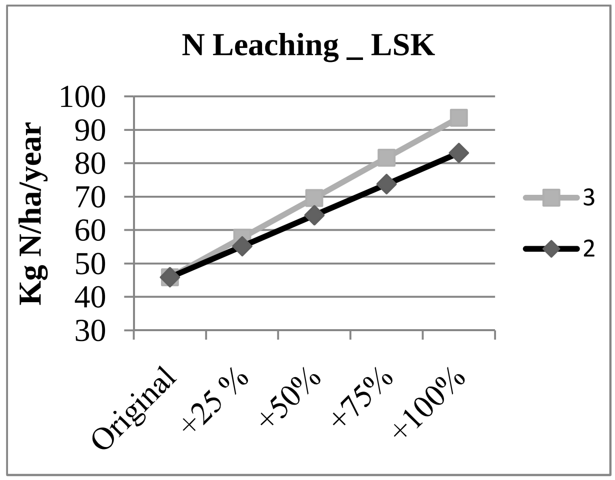



Fig. 5.28 N Leaching for LSK Village

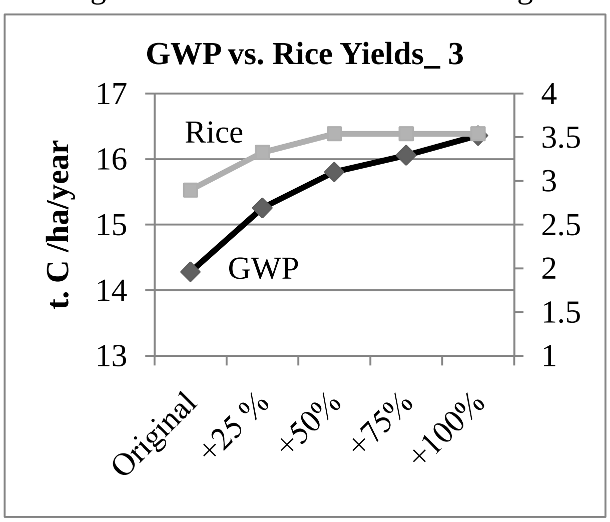



Fig. 5.29 GWP vs. Rice Yields for LSK _ 1

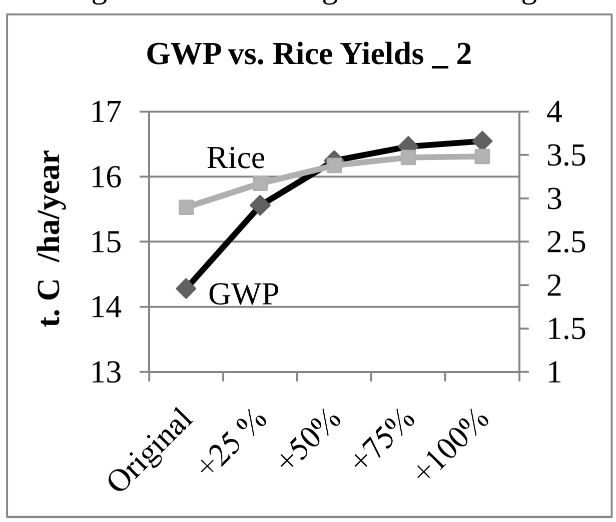



Fig. 5.30 GWP vs. Rice Yields for LSK _2

#### 5.1.3.2 HLX

N deficiency for HLX village decreased significantly since the 1990s (Fig. 5.32, Fig. 5.34), although rice yields in 2009 have doubled since 1991 (Fig. 5.31). This indicates that the increase of N fertilizer application in HLX village generally kept up with growth of N demand, as Fig. 5.33 displayed. It should be said that N balance for HLX village has been improved since the 1990s and there was no severe N deficiency problem in the village in 2009. So, for this village, N regulation and N fertilizer input increase were both tested to assess nitrogen balance for this village. Also, since HLX did not apply any manure in paddy field, this experiment will assess what would happen if part of N fertilizer were replaced by manure. Specifically, 25% and 50% of the current N application will be replaced by manure with equivalent N contained.

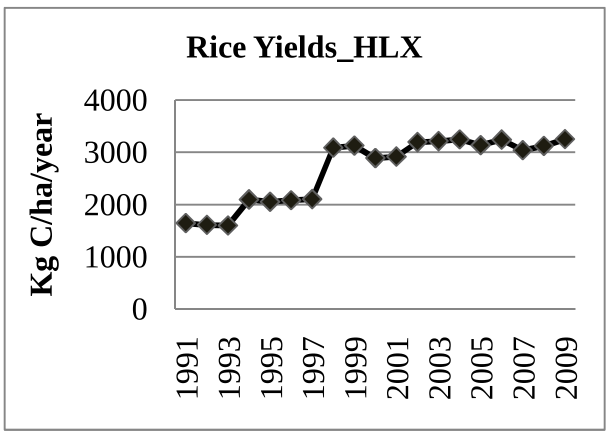



Fig. 5.31 Rice Yields for HLX Village

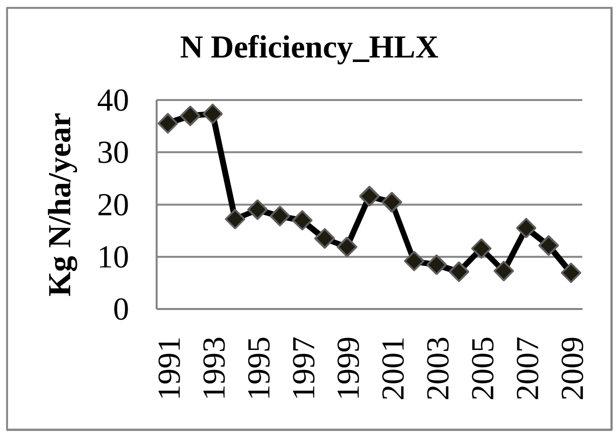



Fig. 5.32 N Deficiency for HLX Village

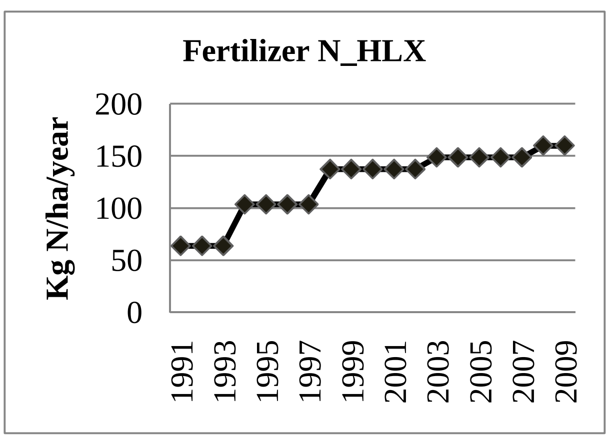



Fig. 5.33 Fertilizer N for HLX Village

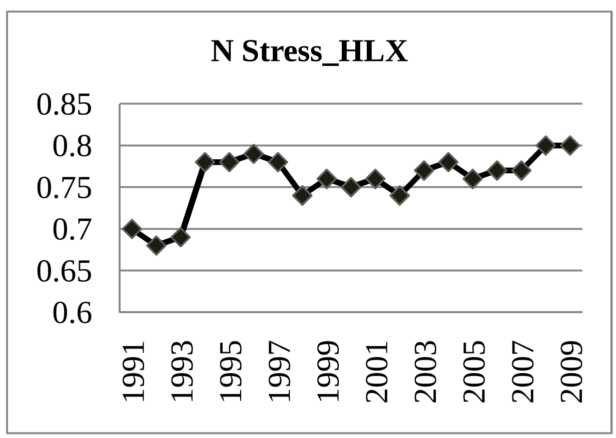



Fig. 5.34 N Stress for HLX Village (unitless)

In Fig. 5.35, rice yields increased less than 1% even when 50% more N fertilizer was applied, but rice yields decreased 25.6 % when N fertilizer input decreased 50%. GWP values decreased in a manner similar to rice yields if N input decreased; but GWP values increased about 6% when N fertilizer increased 50%, which is more significant than the change in rice yields. This means current N fertilizer application is generally reasonable and potential N regulations would disturb N balance in the area. Furthermore, replacing N fertilizer with manure will also decrease rice yields, as Fig. 5.36 displayed, but net greenhouse gas emissions will be mitigated too. This indicates that if reducing GWP values is more important than keeping high rice yields, then it will be helpful to replace at least part of N fertilizer with manure.

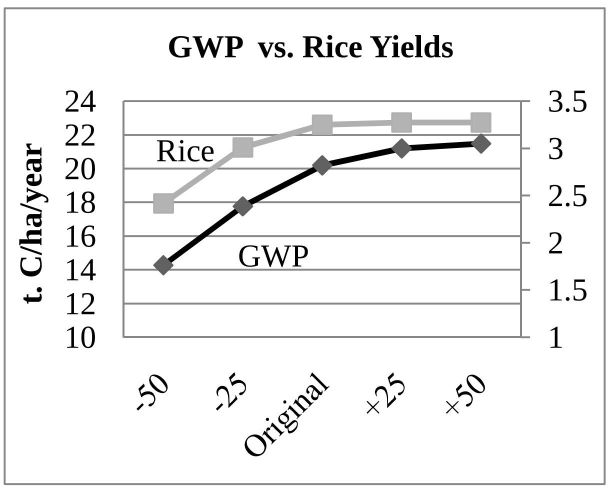


Fig. 5.35 GWP vs. Rice Yields for HLX-1

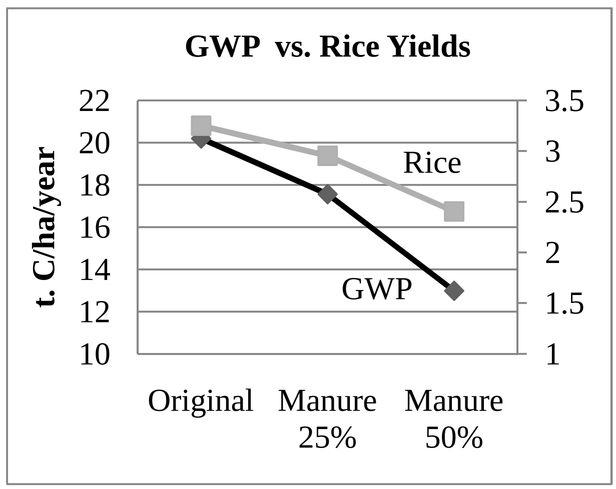


Fig. 5.36 GWP vs. Rice Yields for HLX-2

**5.1.3.3 LC**

Modeling results (Fig. 5.38, Fig. 5.40) for LC village show that the N deficiency problem for this village had improved from 1995 to 2000, but it has been getting worse after that. The reason is N fertilizer application (Fig. 5.39) increased quickly around 2000 but then remained almost unchanged. Even worse, farmers in this area did not apply manure anymore after 2000; this will reduce soil N storage. As a result, N deficiency increased quickly, while rice yields (Fig. 5.37) did not increase significantly. Therefore, it would be a good idea for this village to increase N fertilizer application since N input is apparently insufficient to meet crop growth demand.

Experiments conducted for this village are similar to those for LSK village. Additional N fertilizer was added to paddy field using two proportions. In Fig. 5.41 and Fig. 5.42, the light gray stands for N divided into three applications (M3) and the dark line for two (M2). Fig. 5.41 displays the different effects of the two methods in regards to rice yields: M 3 resulted in higher rice yields, but the difference between M3 and M2 is not significant, and the two methods share close results when N application increased more than 75%. However, the difference between the two methods is more noticeable in Fig. 5.42. N leaching of M 3 did not change much when N application increased less than 50%, while N leaching of M 2 increased consistently when N application increased. Nonetheless, N leaching of M 3 increased quickly after the 50% threshold, and exceeded N leaching of M2 when N application increased more than 75%. Patterns of GWP values for the two methods are also very different: For M2 (Fig. 5.43), GWP values increase along with rice yields, but M3's GWP values (Fig. 5.44) decreased at first and then increased when N application increased more than 50%. Both figures (Fig. 5.43, Fig. 5.44) indicate that rice yields will not increase much when N application increases more than 75% but GWP values will increase quickly after the 75% level. In this case, it would be possible for LC to increase rice yields without aggravating environmental pollution if increased N did not exceed 50%.

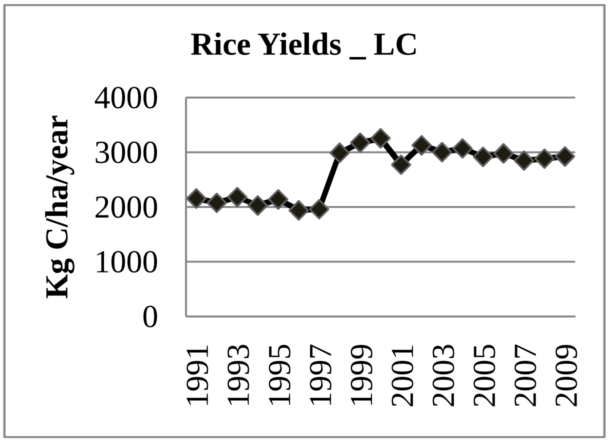



Fig. 5.37 Rice Yields for LC Village

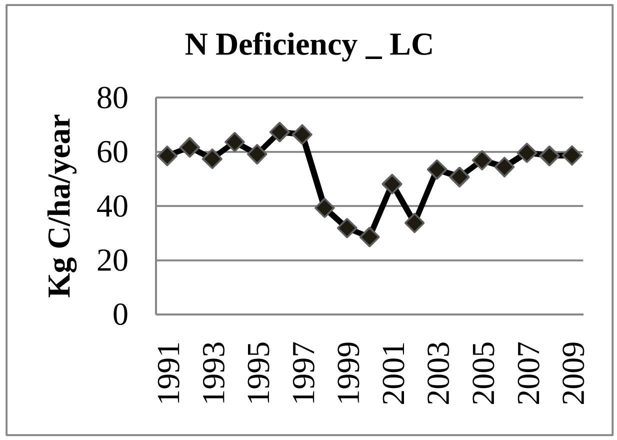



Fig. 5.38 N Deficiency for LC Village

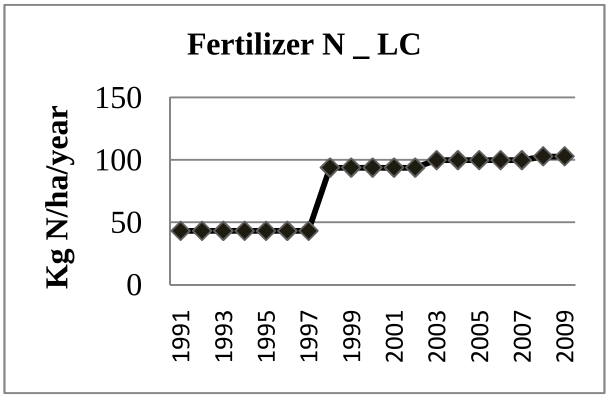



Fig. 5.39 Fertilizer N for LC Village

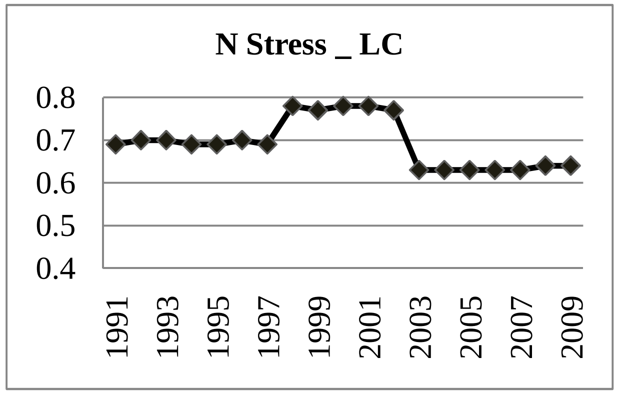



Fig. 5.40 N Stress for LC Village

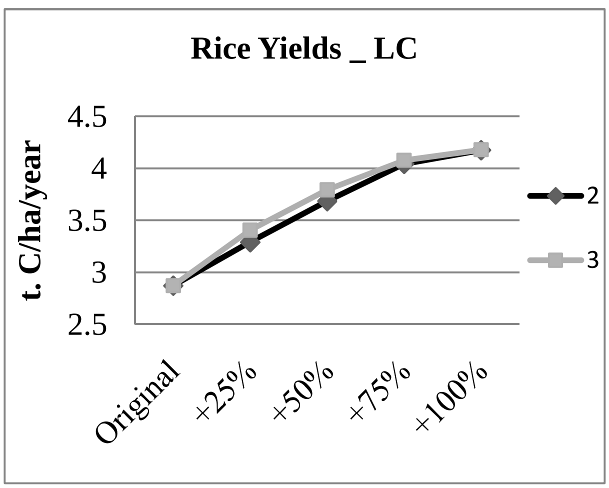



Fig. 5.41 Rice Yields for LC Village

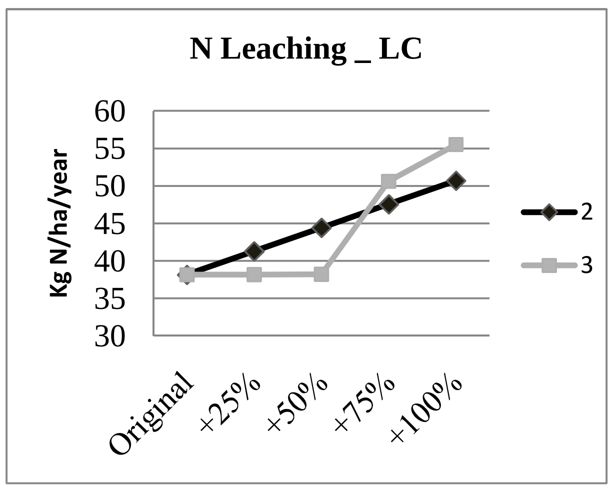



Fig. 5.42 N Leaching for LC Village

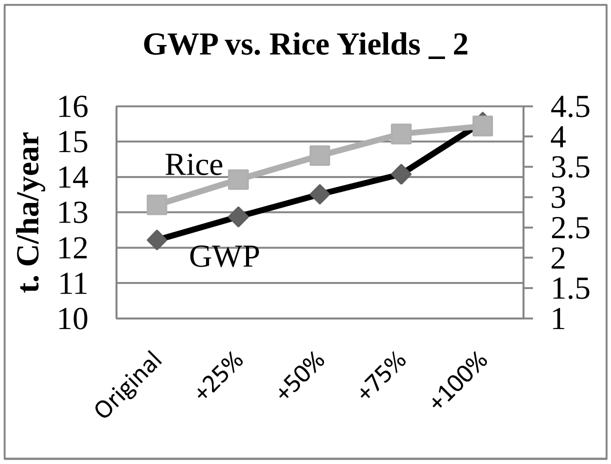



Fig. 5.43 GWP vs. Rice Yields for LC_ 1

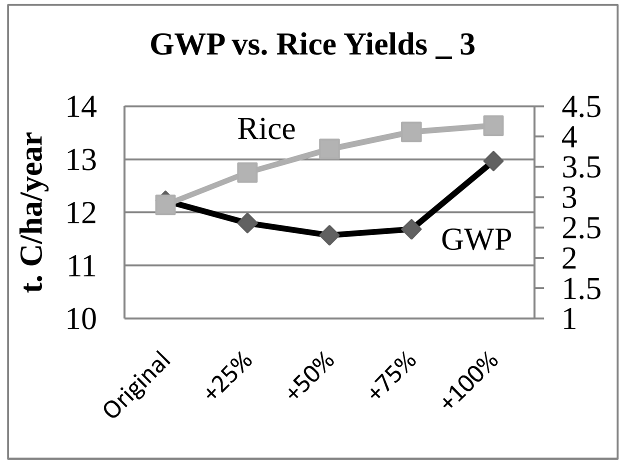



Fig. 5.44 GWP vs. Rice Yields for LC_2

**5.1.3.4 XCB**

N deficiency (Fig. 5.46, Fig. 5.48) for XCB village increased from 1991 to 2005 and then decreased significantly after 2007. Fertilizer input (Fig. 5.47) did not catch up with rice yield growth (Fig. 5.45) before 2005, but fertilizer N input after 2005 increased from 62.63 kg N/ha/year to 132.63 kg N/ha/year. As a result, N deficiency was almost removed in 2009. Farmers in this study zone increased their N fertilizer input possibly because they could afford more fertilizer than before, and additional N application will help them to increase rice yields. As Fig. 5.45 displays, rice yields did increase from 2137 kg C/ha in 2005 to 2690 kg C/ha in 2009. However, this does not mean that rice yields will always increase quickly with additional N application. Fig. 5.49 displays that rice yields increased only 24 kg C/ha even if 50% more N fertilizer was applied than current practice, but reducing N application by 50% resulted in 730 kg C/ha rice yield loss. Fig. 5.50 displays the results from an experiment that replaced part of input N fertilizer with manure, with N input amounts equivalent to current practice. It indicates that using manure is helpful to decrease GWP values, but rice yields will decrease at the same time. In general, modeling results indicate that N fertilizer application in 2009 is reasonable and N regulation in this study area will hurt farmers since reduced N application will cause unnecessary rice loss.

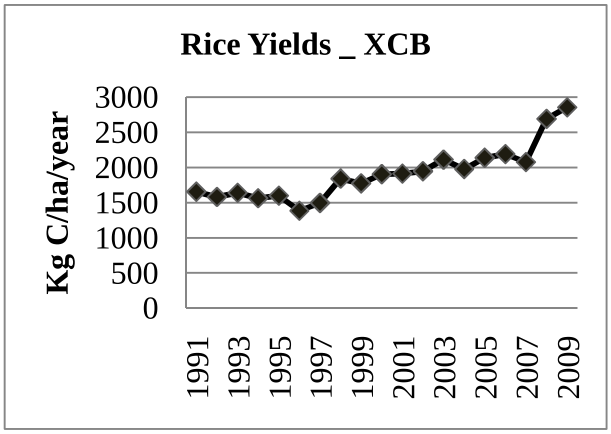



Fig. 5.45 Rice Yields for XCB Village

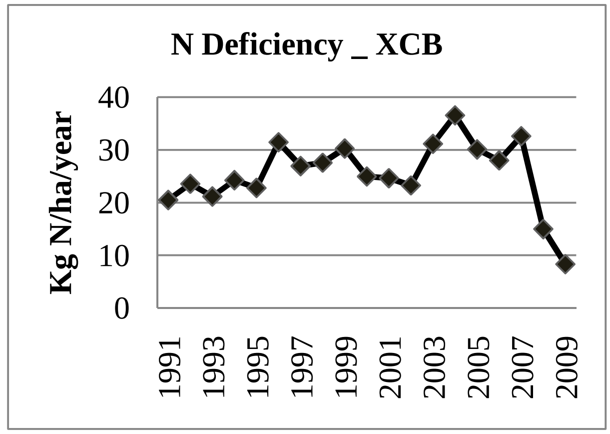



Fig. 5.46 N deficiency for XCB Village

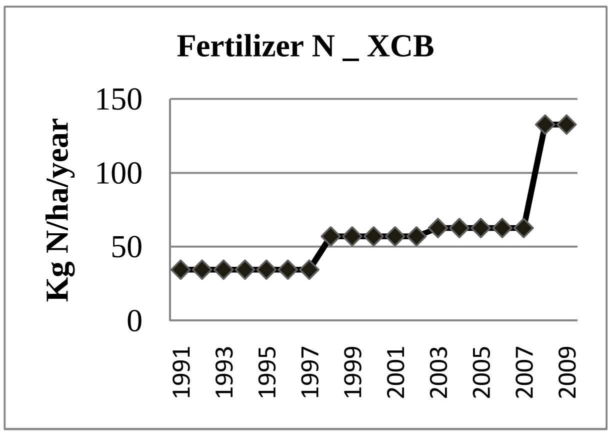



Fig. 5.47 Fertilizer N for XCB Village

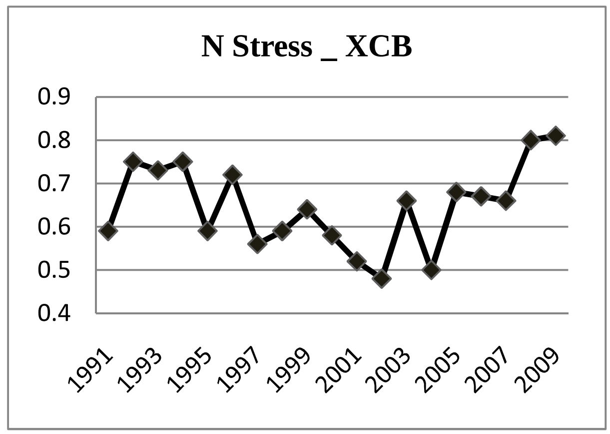



Fig. 5.48 Fertilizer N for XCB Village

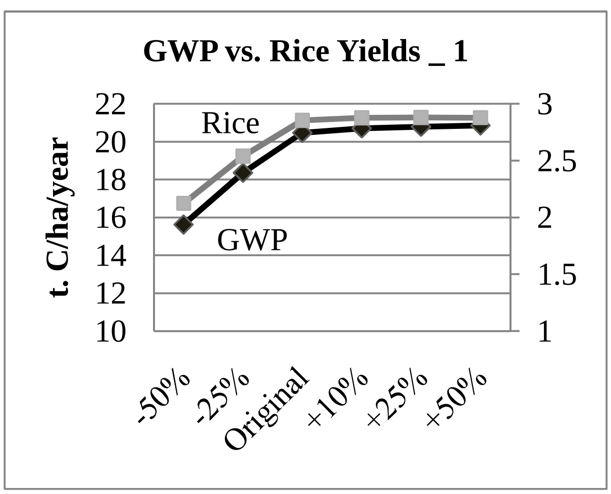



Fig. 5.49 GWP vs. Rice Yields for XCB _ 1

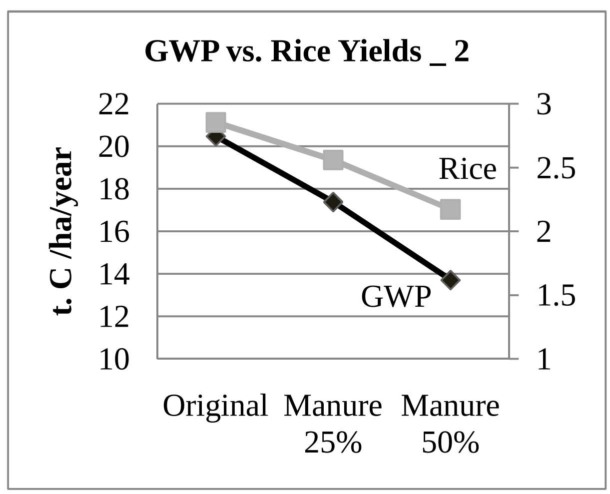



Fig. 5.50 GWP vs. Rice Yields for XCB _ 2

## 5.2 SPATIAL INTERPOLATION

In this study, results obtained from the DNDC model were simulated at the village level. This is helpful to understand the diversity of farming practices and crop growth environments in a county, and also identify spatio-temporal variations of nitrogen loss from paddy field. Ideally, one would cover all villages in the county to obtain more accurate estimation for a region, but time and budget limitations make it impractical to do so. In light of the difficulty of collecting farming practice data in China, previous studies adopted the county as the finest spatial unit for their regional agriculture ecosystem studies (Li et al. 2005). However, this study found that differences between villages, even within the same county, in regards to N usage and N efficiency, could be significant. Thus it is necessary for researchers to obtain an initial estimation at the village level. However, there is a need to understand or estimate crop growth and N efficiency for large regions, such as a county or a province; and that can be achieved through many approaches. In this study, three experiments were designed and conducted to compare three possible approaches as discussed in the methods chapter.

As stated before, there are 18 study zones in Anji County, and three of them (ID=3, ID=12, ID=16) were selected as designed. Results obtained from the three experiments for those zones have been displayed in the form of tables (Table 5.1, 5.2 and 5.3). The units for Carbon change, $CH_4$ and Rice yields are the same, which is kg C/ha/year. All other fields related to N circulation share the same unit – kg N/ha/year. Specifically, N_UP means nitrogen taken by paddy rice and N_LH means N leaching from paddy field. The title of % means the difference of values between three experiments in percentage. The equations listed below, using Rice Yields as an example, illustrated items in the three tables.

**Definitions**:

Rice Yields A: rice yields from experiment A (kg c/ha/year)

Rice Yields B: rice yields from experiment B (kg c/ha/year)

Rice Yields C: rice yields from experiment C (kg c/ha/year)

B- A: difference of rice yields between experiment B and A

C-A: difference of rice yields between experiment C and A

C-B: difference of rice yields between experiment C and B

% : difference of rice yields between experiments in percent

Equations:

B-A %=( Rice Yields B- Rice Yields A) * 100/Rice Yields A

C-A %=( Rice Yields C- Rice Yields A) * 100/ Rice Yields A

C-B %=( Rice Yields C- Rice Yields B) *100/ Rice Yields B

Table 5.1 Experiments Comparison for Zone 3

| ID | Rice yields | % | Carbon change | % | $CH_4$ | % | N_UP | % | N_LH | % | $N_2O$ | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 2580 | | -241.2 | | 55.0 | | 94.3 | | 1.8 | | 4.0 | |
| B | 2402 | | -889.6 | | 91.0 | | 87.0 | | 66.0 | | 6.5 | |
| C | 2485 | | -890.0 | | 95.0 | | 90.3 | | 54.7 | | 6.7 | |
| B-A | -178 | -6.9 | -648.4 | 268.8 | 36.0 | 65.5 | -7.3 | -7.8 | 64.2 | 3568.3 | 2.5 | 62.9 |
| C-A | -95 | -3.7 | -648.8 | 269.0 | 39.9 | 72.6 | -4.0 | -4.3 | 52.9 | 2938.9 | 2.7 | 68.4 |
| C-B | 83 | 3.5 | -0.4 | 0.0 | 3.9 | 4.3 | 3.3 | 3.8 | -11.3 | -17.2 | 0.2 | 0.03 |

Table 5.2 Experiments Comparison for Zone 12

| ID | Rice yields | % | Carbon change | % | $CH_4$ | % | N_UP | % | N_LH | % | $N_2O$ | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 3142 | | -427.2 | | 138.0 | | 116.5 | | 48.0 | | 7.1 | |
| B | 3140 | | -2.0 | | 93.6 | | 116.5 | | 45.9 | | 5.8 | |
| C | 3139 | | 6.0 | | 99.8 | | 116.4 | | 45.3 | | 6.3 | |
| B-A | -3 | -0.1 | 425.2 | -99.5 | -44.4 | -32.8 | 0.0 | 0.0 | -1.8 | -3.8 | -1.3 | -18.2 |
| C-A | -3 | -0.1 | 433.2 | -101.4 | -38.2 | -27.7 | -0.1 | -0.1 | -2.1 | -4.4 | -0.8 | -11.8 |
| C-B | -1 | -0.0 | 8.0 | -403.0 | 6.2 | 6.6 | -0.1 | -0.1 | -0.3 | -0.6 | 0.5 | 7.9 |

Table 5.3 Experiments Comparison for Zone 16

| ID | Rice yields | % | Carbon change | % | $CH_4$ | % | N_UP | % | N_LH | % | $N_2O$ | % |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 1793 | | 751.0 | | 235.6 | | 66.0 | | 41.2 | | 6.2 | |
| B | 1823 | | 866.4 | | 237.6 | | 67.2 | | 49.7 | | 5.7 | |
| C | 1797 | | 898.2 | | 213.0 | | 66.2 | | 44.7 | | 5.7 | |
| B-A | 30 | 1.7 | 115.5 | 15.4 | 1.9 | 0.8 | 1.2 | 1.8 | 8.4 | 20.5 | -0.5 | -8.3 |
| C-A | 4 | 0.2 | 147.2 | 19.6 | -22.7 | -9.6 | 0.2 | 0.3 | 3.5 | 8.5 | -0.4 | -7.3 |
| C-B | -26 | -1.4 | 31.8 | 3.7 | -24.6 | -10.4 | -1.0 | -1.4 | -4.9 | -9.9 | 0.1 | 1.1 |

Experiment A is the most convenient method, since it simply selected results from site-based modeling to present each of the 18 study zones that were defined by Thiessen polygons. However, this method can not reflect the spatial variation of soil properties in a study zone, although farming practice and climate conditions were assumed to be the same within that zone. In an effort to include the diversity of soil properties, experiments B and C were designed. Instead of using the soil properties of a certain site directly, experiment B adopted area-weighted average soil properties to run the DNDC model. Experiment C took each soil type that has paddy field in the same study zone, and then averaged site-based modeling results for each soil type, using areas of paddy field in each soil type as the weighting factor.

From the three tables above (Table 5.1, 5.2 and 5.3), readers can find that the difference between experiments generally decreased from zone 3 to zone 12 and zone 16. Also, the difference between experiment B and C is not significant in all three zones; while the difference between these two methods and experiment A is much more noticeable. In this case, it seems that there is no significant difference between results obtained from experiment B and C. However, within each zone, particular items are not equally sensitive to changes in soil properties. For example, rice yields are less sensitive than carbon balance and $CH_4$ emissions. Rice yields did not change much between three experiments in all three zones, while $N_2O$ emissions and N leaching varied considerably. This suggests that if the main purpose of a study is to obtain rice yields or N uptake capacity of paddy rice, then it is possible to simply use site- based simulation results to estimate regional rice production. However, selecting an interpolation approach will be a key factor if other items, such as carbon balance and N leaching, were included in research objectives, and the difference between approaches will vary in different zones as the three tables indicate.

If all paddy field in the same study zone received the same set of farming practice and climate data, what caused the different results between the three experiments? Experiment A used soil properties at selected sites directly, while experiment B adopted weighted average soil properties, using area of paddy field as the weighting factor. Experiment C ran the model on each soil type within the same study zone then averaged the results from all soil types using area of paddy field as the weighting factor. It is relatively easier to compare experiments A and B, because the only difference between them is the input of soil properties. Table 5.4, Table 5.5 and Table 5.6 display the difference between experiment A and B for three zones. Entries in the "Site" row are soil properties used by experiment A; the row "Average" contains soil properties used by experiment B; the row "Difference" is the soil properties difference between the two experiments and "Percent" is the difference in percentage.

Table 5.4 Soil Properties Difference for Zone 3

| ID | Bulk density | Hydro conductivity | SOC | Clay | Porosity | Field capacity | Wilting point | pH |
|---|---|---|---|---|---|---|---|---|
| Site | 1.416 | 0.029 | 0.012 | 0.319 | 0.476 | 0.336 | 0.197 | 5.15 |
| Average | 1.401 | 0.026 | 0.016 | 0.226 | 0.476 | 0.287 | 0.146 | 5.80 |
| Difference | - 0.015 | -0.003 | 0.004 | -0.094 | 0.000 | -0.049 | -0.051 | 0.65 |
| Percent | -1.05 | -9.76 | 33.38 | -29.39 | 0.07 | -14.56 | -25.73 | 12.56 |

Table 5.5 Soil Properties Difference for Zone 12

| ID | Bulk density | Hydro conductivity | SOC | Clay | Porosity | Field capacity | Wilting point | pH |
|---|---|---|---|---|---|---|---|---|
| Site | 1.389 | 0.259 | 0.017 | 0.206 | 0.482 | 0.284 | 0.136 | 6.0 |
| Average | 1.404 | 0.253 | 0.015 | 0.222 | 0.477 | 0.281 | 0.142 | 6.0 |
| Difference | 0.015 | -0.006 | -0.002 | 0.016 | -0.005 | -0.003 | 0.007 | 0.003 |
| Percent | 1.06 | -2.32 | 8.21 | 7.66 | -1.01 | -0.93 | 5.10 | 0.06 |

Table 5.6 Soil Properties Difference for Zone 16

| ID | Bulk density | Hydro conductivity | SOC | Clay | Porosity | Field capacity | Wilting point | pH |
|---|---|---|---|---|---|---|---|---|
| Site | 1.396 | 0.025 | 0.017 | 0.225 | 0.482 | 0.289 | 0.146 | 6.000 |
| Average | 1.411 | 0.026 | 0.015 | 0.203 | 0.474 | 0.270 | 0.132 | 5.884 |
| Difference | 0.015 | 0.001 | -0.002 | -0.022 | -0.008 | -0.019 | -0.014 | -0.116 |
| Percent | 1.08 | 2.37 | -8.68 | -9.93 | -1.69 | -6.63 | -9.77 | -1.93 |

Table 5.4, Table 5.5, and Table 5.6 indicate that differences of input soil properties between experiment A and B are much more noticeable in zone 3 than the other two zones, but there is no big difference between Zone 12 and Zone 16. This partly explains why the difference between the three experiments is more significant in Zone 3 than the other two, as Table 5.3, Table 5.4 and Table 5.6 indicate. The zone 3 example indicates that the model output can respond to significant change in soil properties input, but it is not appropriate to construct a linear correlation between soil properties and modeling results. For instance, Table 5.6 and 5.5 display that the difference in soil properties is slightly greater in zone 16 than zone 12, but modeling results indicate that the variation is roughly greater in zone 12 than zone 16. This is because the biogeochemical model is a non-linear complex model, and soil properties have to work with other factors, such as farming and climate factor.

## 5.3 DISCUSSION AND SUGGESTIONS

### 5.3.1 Model Results Discussion

Previous studies asserted or suggested that farmers in China, especially in economically developed areas, such as the Yangtze River Delta, have been using too much nitrogen fertilizer for crop needs. Therefore, researchers suggested the government should regulate nitrogen fertilizer usage to avoid serious environmental problems. However, the finest scale for previous regional studies is at or above the county level; a scale which concealed the diversity of fertilizer usage and efficiency within a county. To compensate for that deficiency, this study assessed the spatio – temporal variation of fertilizer application and N efficiency of paddy rice systems within the Anji County in Zhejiang Province, China. The variation was caused by different crop growth environments, which includes anthropogenic activities -- farming practices, and natural environmental conditions -- climate and soil conditions.

Modeling results at the village level in Anji County suggest that it is inappropriate to assume or assert that most farmers in economically developed areas in China have been using too much fertilizer since the 1990s and thus they should reduce N fertilizer application. According to simulation results of this study (Fig. 5.13 and Fig. 5.14), fertilizer application and N efficiency varied significantly among different villages within the same county. In fact, as Fig. 5.6 displays, instead of having too much N in paddy field, some villages actually have experienced serious N deficiency problem between 1991 and 2009. Furthermore, patterns of N deficiency changes for the 18 selected villages can be categorized into four groups, and the causes of their patterns are also different. For this reason, it is important to keep in mind the spatial variation of crop growth environments that include fertilizer application and also natural environment. Also, it is not prudent to simplify the complex farming activities as well as soil and climate conditions in a county by using aggregated statistical datasets and drawing a general conclusion from them because the difference between villages can be significant even within the same county. In fact, both field survey datasets and model simulations indicate that it is not appropriate to simply categorize a county as an environment friendly county or not.

In addition to spatial variation, temporal variation is another important factor. As stated before, greenhouse gas emissions, N efficiency and Carbon balance of paddy rice systems varied significantly between 1991 and 2009. Potential causes should be changes in farming practices and climate conditions. It seems that farming practices have more influence on carbon balance, but climate conditions have much stronger impacts on $CH_4$ and $N_20$ emissions variations, based on the comparison of model results using historical climate files and a single climate file. This suggests that results obtained from field studies can vary greatly between years, and thus it is necessary for researchers to take temporal variation into account before suggesting standards or optimal farming practices to local farmers.

### 5.3.2 Spatial Interpolation Approaches Discussion

Regional modeling is more convenient for quick estimation for a region at or above the county level; due to data and model limitations it misses many details, especially the spatial attributes of crop growth environments. By contrast, study at the site level can simulate agroecosystems better since it will simulate crop systems in detail. With sufficient samples, site-based modeling could reflect the spatial diversity of crop growth environments and negative environment impacts as well. However, time and budget issues could make it impractical to simulate every village in a county. An optimal approach could bridge site- based modeling with regional estimation, since this approach will reserve the advantages of site-based modeling but also meet the demand for large-region estimation. In an effect to achieve this goal, three interpolation approaches were designed and assessed in this study. Basically, these approaches obtained relatively accurate modeling results at the village level, and then those results were interpolated to area data. However, there are two challenges in performing spatial interpolation of site- based modeling results. First is the division of study area. In this research, the county was divided into 18 study zones, which were generated using the locations of 18 villages as the geometric centers for every polygon. Certainly there are other and even better choices, but identifying optimal zonal method is not the focus of this study. Another challenge is the method used to do the interpolation, so this study designed three experiments to make a comparison.

It is not surprising that uncertainty remains in the process of interpolation, no matter which approach is adopted, since the discrepancy between actual situations and estimated results cannot be diminished by statistical methods. Different methods will yield varying results in regional estimations, so it is necessary to assess the sensitivity of site- based modeling results to different interpolation approaches. Experiment results show the various study zones have different responses to the selection of interpolation approaches, as soil diversity and paddy field distribution changes from zone to zone. If paddy field in a zone was relatively evenly distributed across many soil types, as the zone 3 example (Fig. 4.3) shows, then the difference between the three approaches will be significant (Fig 5.1). On the contrary, if most paddy field was located in a certain soil type or a few soil types with similar soil properties, as the zone 12 example (Fig. 4.2) shows, then the impacts of approach selection would be moderate (Fig. 5.2). Furthermore,

Table 5.1, Table 5.2, and Table 5.3 demonstrate that different variables within the modeling, such as greenhouse gas emissions and rice yields, are not equally sensitive to different interpolation approaches.

### 5.3.3 Limitations and Suggestions

Biogeochemical modeling is still far from perfect, and the performance of a certain model will change at different locations since the prototype developed for a model is usually based on a certain area. Although the DNDC model has been widely used and validated, the model itself cannot guarantee the quality of every simulation. The performance of any model largely depends on the quality of input data. But collecting highly reliable data in developing countries, such as China, is still a challenge for researchers. Without exception, data quality is a challenge for this research. Climate, land use, physical soil properties and farming practice are four components required by the DNDC model. Among those components, farming practice data is the most difficult one to collect since there are no publically available official historical records at the village level for reference. This research is not designed to identify or asses input data errors or uncertainty. Although three experiments were designed, this research mainly assessed the sensitivity of modeling results to different interpolation approaches. In these experiments, the impacts of soil diversity and paddy field distribution across soil types were assessed.

In this study, farming practice datasets were collected through field surveys and interviews with local farmers and officers. These first - hand datasets at the village level are essential to understanding the range of crop growth in the county; but the quality of datasets cannot be guaranteed or validated with supplemental datasets. It is relatively easier for farmers to recall their crop management details in recent years, so the simulation results for recent years are more reliable; but it is harder to remember things happened decades ago, and the simulation results for 10 or 20 years would have a higher margin of error.

Besides crop management, climate is another important factor. Original climate files used in this research were obtained from Lanzhou University in China, and were generated through spatial interpolation, using information from ground weather stations in China. Due to legal restraints, data from the weather station in the county is not available to the public, so this study adopted the interpolated climate file and clipped Anji County from the national products. If possible, more accurate climate data would be helpful.

Although the three experiments in this research were designed to identify the sensitivity of modeling results to various spatial interpolation approaches, gaps still existed between sites and regions. First, the paddy field distribution used for this study covers only one year, so the results between years might vary because paddy field distribution might be different too. In addition to this data issue, there are two challenges: the apportioning of sub regions for a study area, and the method used to interpolate results obtained at site scale might be changed. According to Tobler (1970), everything is related to everything else, but near things are more related than distant things. For this reason, a large study area should be divided into smaller regions that share similar attributes. Thiessen polygons, which were generated based on the locations of villages, were used to divide the county into 18 study zones in this study. The method certainly has limitations, since it is not a natural reflection of farming practices for an area. Other possible solutions include utilizing soil polygons or adopting administration boundaries directly, but these methods have limitations too. To identify an optimal partition method, further research is necessary.

This study identified the spatio-temporal variations of fertilizer usage, N efficiency and the associated environmental costs of paddy rice systems in one county. Modeling results suggest that the difference between villages can be significant. For this reason, it is important for policy makers to realize the spatial diversity of crop growth environments and their negative environmental impacts before forming any uniform nitrogen fertilizer regulations because they could hurt farmers and also cause unnecessary loss in rice yields, which might be a threat to China's food security and even social stability. This study indicates that combining biogeochemical modeling and geospatial technology is helpful for researchers and policy makers to understand what happened to paddy field spatio-temporally and then set up more reasonable farming regulations or suggestions that will balance the crop demands and environmental protections more efficiently. Local governments will be able to use methods mentioned in this study to establish a detailed farming practices management system. Also, it would be a good idea for researchers to work with local governments and start a project to record local farming practices in a study area in detail at the village or finer level regularly, since this research has proved the necessity of getting high quality data with fine spatial resolution.

# CHAPTER 6 CONCLUSIONS

## 6.1 OVERVIEW AND MAJOR FINDINGS

Rice is the staple food in China, especially in the south. Over the last twenty years, the level of nitrogen fertilizer applied in fields has been increased considerably to keep up with growing food demand. Researchers (Lishan 1992, Li 2004, Zou et al. 2009) believe this change has been causing a series of environmental consequences, including groundwater pollution, nitrogen leaching, runoff, and greenhouse gas emissions, contributing to the problem of global climate change. Previous studies assumed or concluded that most farmers in economically developed areas in China have been applying too much fertilizer in paddy field for crop needs, so it was suggested that the government should regulate nitrogen fertilizer usage to avoid serious environmental problems. However, previous studies either used results obtained at a few sites to present a large region, such as Yangtze River Delta, or adopted aggregated statistical datasets with a spatial resolution at or above the county level. Both methods failed to tell the spatial diversity of crop growth environments and environmental costs brought by farming activities.

Simulated scenarios in this study indicate that differences in crop growth environments and N efficiency between villages could be significant even within the same county. This research showed that both spatial and temporal factors could bring significant impacts. Modeling results suggested that N efficiency in this county changed dynamically between 1991 and 2009, and each village has a different profile of N fertilizer usage as well as N efficiency. As stated before, the 18 villages in Anji County can be categorized into four groups based on trends of their N use efficiency from 1991 to 2009. Consequently, the strategies for different groups to improve their farming practices should also be customized: some of the villages should increase their fertilizer usage in paddy field, while other villages should improve N use efficiency. Furthermore, if the purpose of a study is to assess greenhouse gas emissions, such as $N_2O$ or $CH_4$, then it is necessary to realize that these emissions not only varied spatially but also changed significantly over time. This study showed that $CH_4$ and $N_20$ emissions are more sensitive to climate variations than changes in farming practices, while Carbon balance is more sensitive to changes in farming practice. Thus, experiments conducted during a certain year may not be suitable for other years, unless they have very close daily weather records.

## 6.2 CHALLENGES AND FUTURE RESEARCH

As stated before, this research showed that both spatial and temporal variation could affect significant impacts in regards to nitrogen use efficiency. Therefore, it is necessary to conduct spatio-temporal studies for paddy rice systems in the future. However, there are several challenges for researchers to promote those studies in China. The first concern is technical: how might future research close the gap between site- based modeling and regional estimation? This study assessed the sensitivity of modeling results to different interpolation approaches, and the results demonstrated that the difference of a study zone's response to the selection of approaches can be significant. This is caused by spatial distribution of paddy rice fields in a study zone. If most paddy field were evenly distributed among several different soil types, the selection of interpolation approach does matter; otherwise the differences in modeling results between three approaches will be moderate. Also, even within a study zone using the same set of farming and climate data, different items related to C and N circulation have differing sensitivities to choices of interpolate approaches. For instance, the difference in rice yield is less than 10% in this study, but that number could be 50% or more for $N_2O$ emission.

Cooperation between researchers, local government and farmers can be challenging, but it is very important and mutually beneficial. This study shows that policy makers can take advantage of spatial technology and biogeochemical modeling to understand the spatial diversity of crop growth environments and their environmental impacts. They could then customize their regulations or policies to fit specific needs at the village level or above, instead of implementing uniform policy across a large region like a province. Also, it will help agencies to project and estimate the potential impacts of their policies on agroecosystems, so unnecessary loss or negative effects could be mitigated. According to this study, the uniform N regulation will hurt farmers and also cause unnecessary rice yield loss. Furthermore, this study shows the potential of using biogeochemical modeling to help improve farming practices. As an illustration, experiments with the four selected villages in Anji County suggested that simply increasing N fertilizer overall would not be as efficient as applying that same increased amount of fertilizer divided in multiple applications. However, it is hard to rely on researchers only to carry out agroecosystem studies in China. As stated before, detailed farming practices and field observation datasets are not publically available, but these high quality datasets are essential to ensure the quality of biogeochemical modeling research. Local governments in China do have the ability to continuously record the required data, and it would be advantageous for everyone if researchers could work with local governments to establish a mutual data sharing mechanism. In summary, modeling researchers, agronomists, farmers and other stake holders need to work together to improve N efficiency in China to better balance crop demands with the need to protect the environment.

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